Southern California Earthquake Center

Final Technical Report

USGS Cooperative Agreement 02HQAG0008

I. Introduction

The Southern California Earthquake Center (SCEC) is a regionally focused organization with a tripartite mission to

- gather new information about earthquakes in Southern California,
- integrate this information into a comprehensive and predictive understanding of earthquake phenomena, and
- communicate this understanding to end-users and the general public in order to increase earthquake awareness and reduce earthquake risk.

SCEC was founded in 1991 as a Science and Technology Center (STC) of the National Science Foundation (NSF), receiving primary funding from NSF's Earth Science Division and the United States Geological Survey (USGS). SCEC graduated from the STC Program after a full 11-year run (SCEC1). It was reauthorized as a free-standing center on February 1, 2002 (SCEC2) with base funding from NSF and USGS. In addition, the Center was awarded major grants from NSF's Information Technology Research (ITR) Program and its National Science, Technology, Engineering, and Mathematics Digital Library (NSDL) program.

This report highlights the Center's research activities during the five-year period (2002-2007), with emphasis on the fifth and final year of SCEC2. The report is organized into the following sections:

II. Planning, Organization, and Management of the Center

The transition from SCEC1 to SCEC2 involved considerable planning and restructuring. A five-year planning document, *The SCEC Strategic Plan 2002-2007*, was submitted to the sponsoring agencies in October, 2001. This plan articulated the Center's long-term research goals. The organization chart of the Center is shown on the next page.

SCEC is an institution-based center, governed by a Board of Directors who represent its members. The SCEC membership now comprises 16 core institutions and 40 participating institutions.

Board of Directors

Under the SCEC2 by-laws, each core institution appoints one board member, and two at-large members are elected by the Board from the participating institutions. The 18 members of the Board are listed in Table II.1.

Table II.1. SCEC Board of Directors

Institutional and At-Large Representatives

Thomas H Jordan* (Chair)	University of Southern California
Gregory C. Beroza* (Vice-Chair)	Stanford University
Peter Bird	University of California, Los Angeles
Emily Brodsky	University of California Santa Cruz
James N. Brune	University of Nevada Reno
Douglas Burbank*	University of California Santa Barbara
Steven M. Day	San Diego State University
James Dieterich	University of California, Riverside
Bill Ellsworth	USGS-Menlo Park
Lisa Grant (At-Large)	University of California Irvine
Thomas Heaton	California Institute of Technology
Thomas A. Herring	Massachusetts Institute of Technology
Lucile Jones*	USGS-Pasadena
J. Bernard Minster*	University of California San Diego
James Rice	Harvard University
Bruce Shaw	Columbia University
Terry Tullis (At-Large)	Brown University
Robert Wesson	USGS-Golden

Ex-Officio Members

Ralph Archuleta (Deputy Director), John McRaney* (Executive Secretary), Mark Benthien (Associate Director, CEO), Phil Maechling (IT Architect)

* Executive Committee members

Ex officio members include the SCEC Deputy Director, Ralph Archuleta; the Associate Director for Administration, John McRaney, who also serves as Executive Secretary to the Board; the Associate Director for Communication, Education and Outreach, Mark Benthien, and the SCEC IT Architect, Phil Maechling.

External Advisory Council

SCEC's Advisory Council (AC) is an external group charged with developing an overview of SCEC operations and giving advice to the Director and the Board. Sean Solomon of the Carnegie Institution of Washington continued as Chair of the AC in 2006. The Advisory Council's second report is reproduced verbatim in Section VI.

Organization of Research

A central organization within SCEC is the Science Planning Committee (PC), which is chaired by the Deputy Director and has the responsibility for formulating the Center's science plan, conducting proposal reviews, and recommending projects to the Board for SCEC funding

The PC membership includes the chairs of the major SCEC working groups. There are three types of working groups—disciplinary committees, focus groups, and special project groups. The Center is fortunate that some of its most energetic and accomplished colleagues participate as group leaders (Table II.2).

Table II.2. Leadership of the SCEC Working Groups

Disciplinary Committees	
Seismology:	John Vidale (chair)*
	Peter Shearer (co-chair)
Geodesy:	Duncan Agnew (chair)*
	Mark Simons (co-chair)
Geology:	Mike Oskin (chair)*
	Tom Rockwell (co-chair)
Fault & Rock Mechanics:	Terry Tullis (chair)*
	Judi Chester (co-chair)
Focus Groups	
Structural Representation:	John Shaw (leader)*
	Jeroen Tromp (co-leader)
Fault Systems:	Brad Hager (leader)*
	Jim Dieterich (co-leader)
	Sally McGill (co-leader)
Earthquake Source Physics:	Ruth Harris (leader)*
	David Oglesby (co-leader)
Ground Motions:	Paul Davis (leader)*
	Robert Graves (co-leader)
Seismic Hazard Analysis:	Ned Field (leader)*
	David Jackson (co-leader)
Special Project Groups	
Implementation Interface:	Paul Somerville (leader)*
	Rob Wesson (co-leader)
SCEC/ITR Project:	Bernard Minster (liaison)*
Borderland Working Group:	Craig Nicholson (chair)*

The Center sustains disciplinary science through standing committees in *seismology*, *geodesy*, *geology*, and *fault and rock mechanics*. These committees are responsible for planning and coordinating disciplinary activities relevant to the SCEC science plan, and they make recommendations to the Science Planning Committee regarding the support of disciplinary infrastructure. Interdisciplinary research is organized into five science focus areas: *structural representation*, *fault* *systems*, *earthquake source physics*, *ground motion*, and *seismic hazard analysis*. The focus groups are the crucibles for the interdisciplinary synthesis that lies at the core of SCEC's mission.

In addition to the disciplinary committees and focus groups, SCEC manages several special research projects, including the Southern California Integrated GPS Network (SCIGN), the Western InSAR Consortium (WInSAR), the Borderland Working Group, and the SCEC Information Technology Research (SCEC/ITR) Project. Each of these groups is represented on the Science Planning Committee by its chair, with the exception of the SCEC/ITR Project, which is represented by Bernard Minster, a Co-P.I. of the project (the P.I. is the Center Director, Tom Jordan).

In June, 2005, the SCEC board voted to disband the SCIGN group as a standing committee of SCEC. SCIGN had completed its mission and the future mainteance of continuous GPS site in southern California will be handled by PBO/UNAVCO, the USGS, and the county surveyors. This action was approved by NSF and the USGS. The transition to PBO maintenance will be completed in March, 2008

The Borderland Working Group represents SCEC researchers interested in coordinating studies of the offshore tectonic activity and seismic hazards in California Borderland. This group will be disbanded at the end of SCEC2.

The goal of the SCEC/ITR Project is to develop an advanced information infrastructure for system-level earthquake science in Southern California. Partners in this SCEC-led collaboration include the San Diego Supercomputer Center (SDSC), the Information Sciences Institute (ISI), the Incorporated Research Institutions for Seismology (IRIS), and the USGS. In many respects, the SCEC/ITR Project presents a microcosm of the IT infrastructures now being contemplated in the context of EarthScope and other large-scale science initiatives, so the opportunities and pitfalls in this area need to be carefully assessed. The SCEC/ITR annual report has been submitted as a separate document to NSF.

A proposal to fund SCEC3 for the period from 2007-2012 was submitted to NSF and USGS in March, 2005. The proposal was approved in 2006 and SCEC continues as SCEC3 under funding for 2007-2012.

Communication, Education, and Outreach

SCEC is committed to applying the basic research in earthquake science to the practical problems of reducing earthquake losses. To accomplish this aspect of its mission, SCEC maintains a vigorous Communication, Education, and Outreach (CEO) Program that receives 10% of its base funding plus other funds from special projects, such as the Electronic Encyclopedia of Earthquakes. CEO activities are managed by the Associate Director for CEO, Mark Benthien. The programmatic elements include structured activities in education and public outreach and two new structures: an *Implementation Interface*, designed to foster two-way communication and knowledge transfer between between SCEC scientists and partners from other communities—in particular, earthquake engineering, risk analysis, and emergency management, and *a Diversity Task Force*, responsible for furthering the goal of gender and ethnic diversity in earthquake science. A report on the third-year CEO activities is given in Section IV.

III. Director's Summary of SCEC2 and Plans for SCEC3

1. Introduction

The Southern California Earthquake Center (SCEC) was established in 1991 under a cooperative agreement between the U.S. National Science Foundation (NSF) and the U.S. Geological Survey (USGS). The SCEC program was renewed for 5-year terms in 2002 (SCEC2) and in 2007 (SCEC3). The Center now involves over 500 scientists at more than 50 institutions.

SCEC's main science goal is to understand the physics of the Southern California fault system using system-level models of earthquake behavior. Southern California's network of several hundred active faults forms a superb natural laboratory for the study of earthquake physics, and its seismic, geodetic, and geologic data are among the best in the world. The region also contains 23 million people, comprising one-half of the national earthquake risk (FEMA, 2000).

Box 1. SCEC Mission

- Gather data on earthquakes in Southern California and elsewhere
- Integrate this information into a comprehensive, physics-based understanding of earthquake phenomena
- Communicate this understanding to society at large and useful knowledge for reducing risk

The Center's mission (Box 1) emphasizes the connections between scientific information gathering, knowledge formation through physics-based modeling, and public communication of hazard and risk.

2. Earthquake System Science

Earthquakes are one of the great puzzles of geoscience. Their study concerns three basic geophysical problems: (a) *the dynamics of fault systems*—how forces evolve within a fault network on time scales of hours to centuries to generate a sequence of earthquakes; (b) *the dynamics of fault rupture*—how forces act on time scales of seconds to minutes when a fault breaks to cause an earthquake; and (c) *the dynamics of ground motions*—how seismic waves propagate from the rupture to shake Earth's surface. These problems are coupled through the nonlinear processes of brittle and ductile deformation. No theory adequately describes the basic features of dynamic rupture, nor is one available that explains the dynamical interactions among faults—we do not yet understand the physics of how matter and energy interact during the extreme conditions of rock failure.

The major research issues of earthquake science are true *system-level problems*: they require an interdisciplinary, multi-institutional approach to model the nonlinear interactions among many fault-system components, themselves often complex subsystems. SCEC attempts to advance earthquake science through a comprehensive program of *system-specific studies* in Southern California. It thus operates on the premise that detailed studies of fault systems in different regions, such as Southern California and Japan, can be synthesized into a generic understanding of earthquake phenomena. International partnerships are clearly necessary to achieve this synthesis.

3. Seismic Hazard Analysis

Probabilistic seismic hazard analysis (PSHA) provides the conceptual and computational framework for SCEC's program earthquake system science. PSHA estimates the probability P_k that the ground motions generated at a geographic site k from all regional earthquakes will exceed some *intensity measure IM* during a time interval of interest, usually a few decades [Cornell, 1968; McGuire, 1995; Field et al., 2002]. Common intensity measures are the peak ground acceleration, the peak ground velocity, and the spectral acceleration at a particular frequency. A plot of P_k as a function of IM is the hazard curve for the k^{th} site, and a plot of IM as a function of site position $\mathbf{x}_k$ for fixed P_k constitutes a seismic hazard map. Seismic hazard maps for Southern California are produced by the USGS National Seismic Hazard Mapping Project

(NSHMP) in collaboration with the California Geological Survey (CGS) and SCEC.

PSHA involves the multiplication and summation of two types of subsystem probabilities: the probability for the occurrence of a distinct earthquake source S_n during the time interval of interest, and the probability that the ground motions at $\mathbf{x}_k$ will exceed intensity *IM* conditional on S_n. The first is obtained from an *earthquake rupture forecast* (*ERF*), whereas the second is computed from an *attenuation relationship* (*AR*), which quantifies the distribution of ground motions with distance from the source.

In Southern California, the *ERF* in the NSHMP-2002 model comprises approximately 13,000 distinct sources, each specified by a fault surface with rupture area A_n and seismic moment magnitude m_n, plus a background seismicity that follows a Gutenberg-Richter distribution [Frankel et al., 2002]. The NSHMP-2002 model is time-independent; i.e., it assumes that earthquakes are randomly (Poisson) distributed in time. Time-dependent *ERF*s have also been constructed to account for the known or estimated dates of previous large earthquakes along the San Andreas fault system, usually based on quasi-periodic renewal models of stress loading and release [WGCEP, 1995, 2003]. The California Earthquake Authority is currently sponsoring a SCEC-USGS-CGS Working Group on California Earthquake Probabilities [WGCEP, 2007] to develop a statewide time-dependent *ERF*, which will be completed in late 2007.

A major SCEC objective is to improve time-dependent *ERF*s through better understanding of earthquake predictability. The SCEC-USGS Working Group on Regional Earthquake Likelihood Models (RELM) is testing of a variety of intermediate-term models [Field et al., 2007]. Based on this experience, SCEC has formed an international partnership extend to scientific earthquake prediction experiments to other fault systems through a global Collaboratory for the Study of Earthquake Predictability (CSEP).

The *AR*s in common use are empirical probability models that relate source and site parameters directly to *IM* values; i.e. the parameters of assumed functional relationships are fit to the available data [e.g., Abrahamson & Shedlock, 1997].

A second major objective of the SCEC program is to develop physics-based *AR*s which correctly model a number of key phenomena that are difficult to capture through this empirical approach. The phenomena include the amplification of ground motions in sedimentary basins, source directivity effects, and the variability caused by rupture-process complexity and three-dimensional (3D) geologic structure. Numerical simulations of ground motions play a vital role in this area of research, comparable to the situation in climate studies, where the largest, most complex general circulation models are being used to predict the hazards and risks of anthropogenic global change.

4. SCEC Organization

SCEC began as an NSF Science and Technology Center in 1991. The SCEC founders, led by its first director, the late Professor Keiiti Aki, articulated a powerful vision for the Center's research program: disciplinary groups would work together to synthesize a "master model" for seismic hazards for Southern California [Aki, 2002; Henyey et al., 2002]. The main components in current master model are represented in Figure 1. SCEC is an institution-based center, composed of core and participating institutions (Table III.1). The core institutions (currently 16) are committed to SCEC's mission and offer sustained support for its programs; the participating institutions (currently 40) are self-nominated through their members' participation and approved by the SCEC Board of Directors. The size of the SCEC community can be measured by the active participants on SCEC projects (656 in 2006) and the registrants at the annual meeting of the SCEC collaboration (414 in September, 2006). Annual meeting registrations for SCEC's entire 16 year history illustrate the growth of the Center (Figure 2).

Table III.1. SCEC Member Institutions (September, 2006)

Core Institutions (16)	Participating Institutions (40)
California Institute of Technology Columbia University Harvard University Massachusetts Institute of Technology San Diego State University Stanford University U.S. Geological Survey, Golden U.S. Geological Survey, Menlo Park U.S. Geological Survey, Pasadena University of California, Los Angeles University of California, Riverside University of California, San Diego University of California, Santa Barbara University of California, Santa Cruz University of Nevada, Reno University of Southern California (lead)	Arizona State University; Boston University; Brown University; Cal-State, Fullerton; Cal-State, Northridge; Cal-State, San Bernardino; California Geological Survey; Carnegie Mellon University; Case Western Reserve University; Central Washington University; CICESE (Mexico); ETH (Switzerland); Institute of Earth Sciences of Academia Sinica (Taiwan); Institute of Geological and Nuclear Sciences (New Zealand); Jet Propulsion Laboratory; Lawrence Livermore National Laboratory; National Chung Cheng University (Taiwan); National Taiwan University (Taiwan); National Central University (Taiwan); Ohio State University; Oregon State University; Pennsylvania State University; Rensselaer Polytechnic University; Rice University; SUNY Stony Brook; Texas A&M University; UC, Berkeley; UC, Davis; UC, Irvine; University of Colorado; University of Kentucky; University of Massachusetts; University of New Mexico; University of Oregon; University of Utah; University of Western Ontario; URS Corporation; Utah State University; Whittier College; Woods Hole Oceanographic Institute

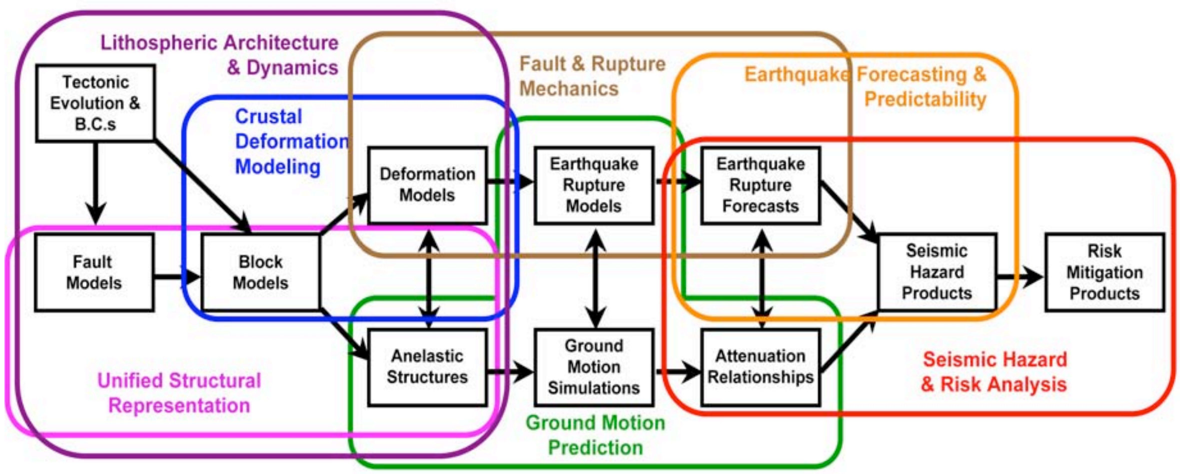

Figure 1. The main components in SCEC's master model for earthquake system science (black boxes), showing the overlapping areas of interest of its interdisciplinary focus groups (colored boxes).

The Center is open to any credible scientist from any research institution interested in collaborating on the problems of earthquake science. However, its program is structured to achieve prioritized science objectives, and its resources are allocated accordingly. Research projects are supported on a year-to-year basis by a competitive, collaboration-building process. In 2005, for example, SCEC sponsored 123 projects involving 156 principal investigators at 51 institutions. There are a number of additional investigators from the USGS, as well as many collaborators supported by SCEC's many partner organizations (Figure 3).

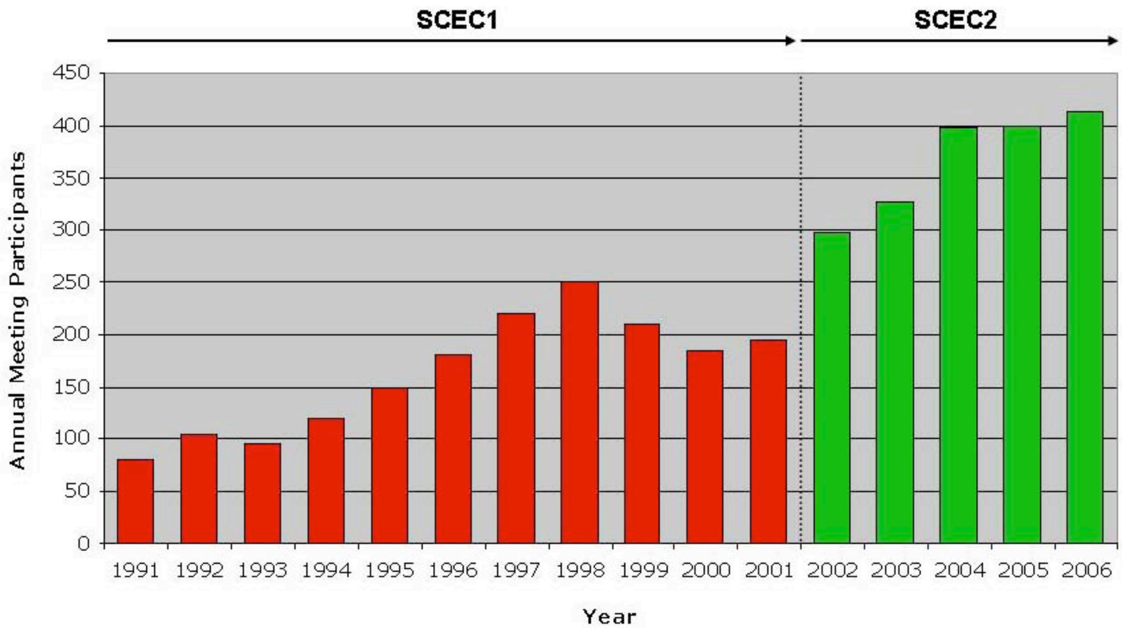

Figure 2. Number of registrants at SCEC Annual Meetings from 1991 to 2006.

SCEC sustains disciplinary science and related data-gathering activities through standing committees in *Seismology*, *Tectonic Geodesy*, and *Earthquake Geology* (Figure 4). Interdisciplinary research is organized into seven science focus areas: *Lithospheric Architecture and* Dynamics, *Unified Structural Representation*, *Fault and Rupture Mechanics*, *Crustal Deformation Modeling*, *Earthquake Forecasting and Predictability*, *Ground Motion Prediction*, and *Seismic Hazard and Risk Analysis*. It maintains an active set of partnerships with earthquake engineering and emergency management organizations through its *Implementation Interface*. The Center's interdisciplinary focus groups and implementation interface are organized to translate knowledge of earthquake systems into seismic hazard products that can be used to reduce earthquake risk (Figure 1).

SCEC2 was led by a Center Director (T. Jordan, USC), who chaired the Board of Directors, and a Deputy Director (R. Archuleta, UCSB), who chaired the Planning Committee. The Board members are representatives appointed by each core institution plus two at-large members elected from the participating institutions. The Planning Committee comprises the 15 working group leaders; it is responsible for reviewing the internal proposals and formulating an annual collaboration plan for distributing resources to projects within the working groups. The Center's external Advisory Council is charged with developing an overview of SCEC operations and advising the Director and the Board (Figure 4).

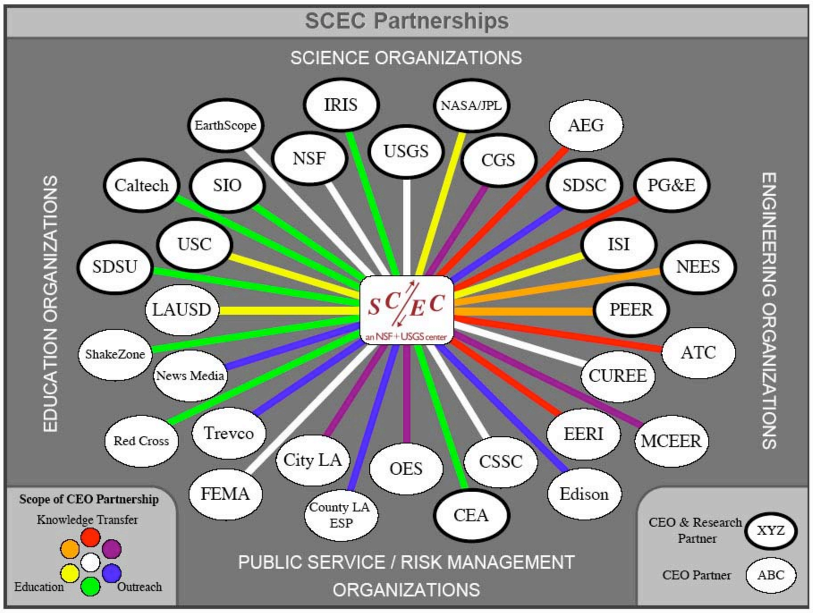

Figure 3. SCEC's active partnerships with other organizations, positioned according to their mission. The connections are color coded by the type of partnership; e.g., a white connector indicates collaboration in all three areas—knowledge transfer, education, and outreach. Research partners are indicated by bold black borders.

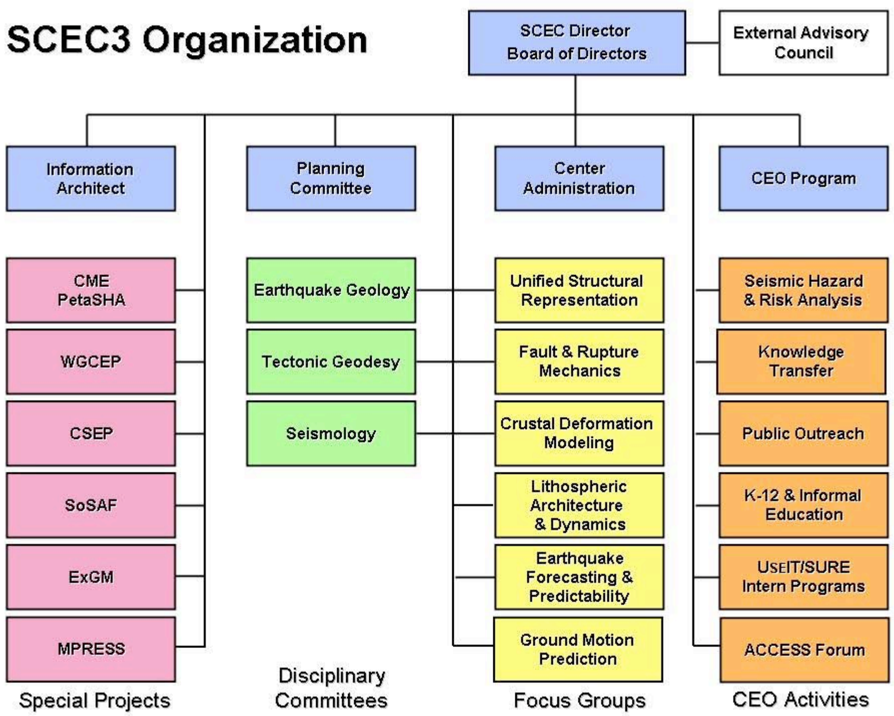

Figure 4. The SCEC3 organization chart, showing the disciplinary committees (green), focus groups (yellow), special projects & operations (pink), CEO activities (orange), management offices (blue), and its external advisory council (white).

5. Science Accomplishments

SCEC and its partners have accelerated the understanding of seismic hazards in Southern California and elsewhere. The results have been incorporated into practical products, such as the National Seismic Hazard Map and its upcoming 2007 revision, as well as the new seismic attenuation relations developed by the Next Generation Attenuation (NGA) Project, which is managed by the Lifelines Program of the Pacific Earthquake Engineering Center. The Center coordinated the development of the 250-station Southern California Integrated GPS Network (SCIGN), the Western InSAR Consortium (WInSAR), the Southern California Earthquake Data Center, and other infrastructure elements for regional earthquake science. SCEC's achievements contributed to the launching of NSF's EarthScope initiative in 2003. For example, SCIGN served as a prototype for EarthScope's Plate Boundary Observatory.

Many of SCEC2 research accomplishments lie in six problem areas central to the earthquake system science. Some highlights are noted below in each area; more extensive descriptions and references can be found in the SCEC annual reports (http://www.scec.org/documents/).

Fault mechanics. New types of laboratory experiments have helped to elucidate the frictional resistance during high-speed coseismic slip, and these data have been combined with field studies on exhumed faults to develop better models of dynamic rupture.

Earthquake Rupture Dynamics. Codes for 3D dynamic rupture simulation have been verified by cross-comparison exercises; they are being validated by comparisons with laboratory experiments and data from real earthquakes, and they have been coupled with anelastic wave propagation models to investigate strong ground motions.

Structural Representation. The Community Velocity Model (CVM) has been improved by extending and refining its 3D elastic structure and incorporating attenuation parameters. A new Community Fault Model (CFM) representing more than 160 active faults has been developed and extended to a Community Block Model (CBM). A prototype Unified Structural Representation (USR) is merging the CVM into the CBM structural framework.

Fault systems. New deformation signals have been discovered by InSAR and GPS, and new data from SCIGN and GPS campaigns have been incorporated into the Crustal Motion Map (CMM). The geologic record of fault-system behavior has been significantly expanded; tectonic block models have been created for physics-based earthquake forecasting, and finite-element codes have been developed for a new CBM-based deformation model that will assimilate the CMM and geologic data.

Earthquake forecasting. Paleoseismic data and data-synthesis techniques have been used to constrain earthquake recurrence intervals, event clustering, and interactions among faults. Relocated seismicity has mapped new seismogenic structures and provided better tests of earthquake triggering models. Regional earthquake likelihood models have been formulated for use in PSHA and earthquake predictability experiments, and they are being tested for prediction skill using a rigorous methodology.

Ground motion prediction. Earthquake ground motions have been simulated using the CVM, realistic source models, and validated wave-physics codes. High-frequency stochastic methods have been combined with low-frequency deterministic methods to attain a broadband (0-10 Hz) simulation capability. Broadband predictions have been tested against precarious-rock data. Simulations have been used to improve attenuation relationships and create realistic earthquake scenarios.

6. The SCEC Collaboratory

Modeling of earthquake dynamics is one of the most difficult computational problems in science. Taken from end to end, the problem comprises the loading and eventual failure of tectonic faults, the generation and propagation of seismic waves, the response of surface sites, and—in its application to seismic risk—the damage caused by earthquakes to the built environment. This chain of physical processes involves a wide variety of interactions, some highly nonlinear and multiscale.

In 2001, SCEC was funded by the NSF Information Technology Research Program to develop a cyberinfrastructure for physics-based modeling of earthquake processes. This Community Modeling Environment (CME) now provides geoscientists and computer scientists with a collaboratory to simulate earthquake processes using high-performance computing facilities and advanced information technologies (Figure 5). The terascale simulations have already delivered new (and worrisome) predictions about seismic hazards from California's San Andreas fault system [Olsen et al., 2006].

The CME collaboration, working within a much larger SCEC community, is providing the cyberinfrastructure to transform PSHA into a more physics-based science. The simulations needed for physics-based SHA can be organized into a set of computational pathways [Jordan & Maechling, 2003]. For example, the pathway for conventional PSHA is to compute an *IM* from an *AR* using sources from an *ERF*, schematically represented as:

Pathway 1: $ERF \rightarrow AR \rightarrow IM$

In physics-based PSHA, intensity measures are calculated directly from the ground motion: $GM \rightarrow IM$. The ground motion is predicted from 4D simulations of *dynamic fault rupture* (*DFR*) and *anelastic wave propagation* (*AWP*). In some cases, especially for sites in soft soils, a *nonlinear site response* (*NSR*) may be included in the ground-motion calculations. The complete computational pathway can thus be written as

$DFR \leftrightarrow AWP \rightarrow NSR \rightarrow GM$.

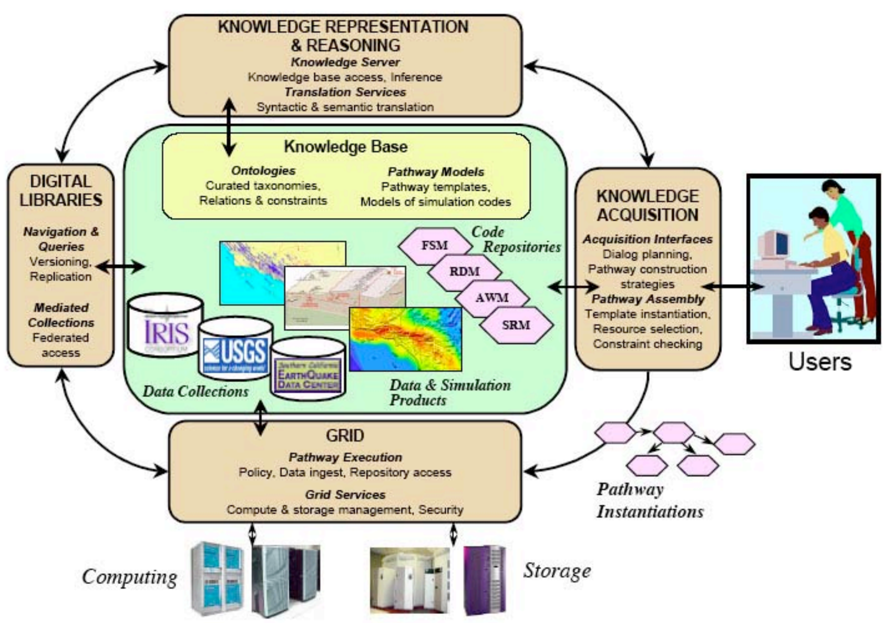

Figure 5. The SCEC Community Modeling Environment is a collaboratory that applies advanced information technologies in knowledge acquisition, grid computing, digital libraries, and knowledge representation and reasoning (outside boxes) to earthquake system science.

The double-arrow indicates that rupture propagation on a fault surface is dynamically coupled to the seismic radiation in the crustal volume containing the fault. However, the *DFR* can usually be represented by an equivalent *kinematic fault rupture* (*KFR*). Therefore, the earthquake calculation can be split into the simulation of ground motions from a kinematic source,

Pathway 2: $KFR \rightarrow AWP \rightarrow NSR \rightarrow GM,$

and the dynamic rupture simulation,

Pathway 3: $DFR \leftrightarrow AWP \rightarrow KFR.$

The source descriptions S_n for the *ERF*s used in conventional PSHA do not contain sufficient information for physics-based PSHA. In addition to the rupture area A_n and magnitude m_n, the *KFR* for Pathway-2 simulations must specify the hypocenter, the rupture rise-time and velocity distributions, and the final slip distribution. Stochastic rupture models that reproduce the variability observed in these parameters for real earthquakes are a major topic of seismological research [Guatteri et al., 2004]. Pathway-3 simulations are an important tool for investigating the stochastic aspects of dynamic ruptures, and they can be used to constrain an "extended" earthquake rupture forecast, *ERF**, which specifies a complete set of the *KFR* probabilities. The physics-based PSHA calculation can then be written as

Pathway 1:* $ERF^* \rightarrow AR^* \rightarrow IM,$

where *AR** is the attenuation relationship obtained from the Pathway-2 simulations.

Instantiation of the 4D simulation elements requires information about the 3D geologic environment. For example, *DFR* depends on the fault geometry, the mechanical properties on both sides of the fault surface, and the stress acting on the fault, whereas *AWP* depends on the density, seismic velocities, and attenuation factors throughout the lithospheric volume containing the source and site. The databases needed to represent the 3D geologic environment for the complete *GM* simulation defines a *unified structural representation* (*USR*).

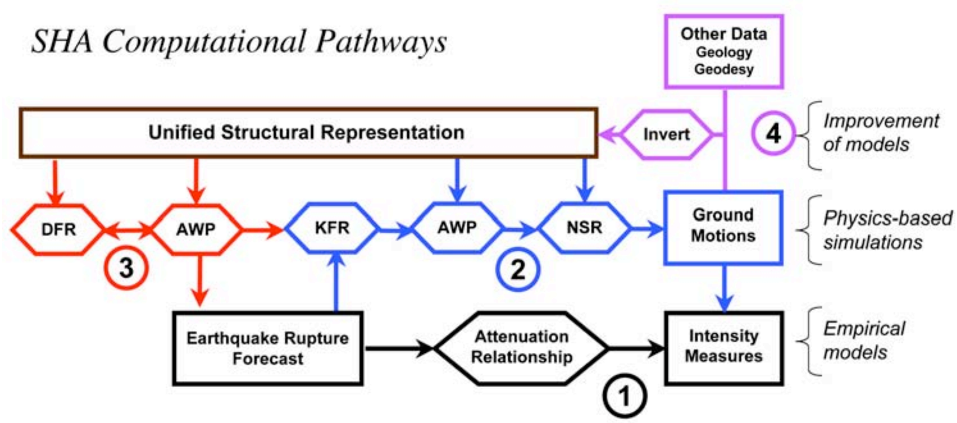

Figure 6. Computational pathways for seismic hazard analysis, using notation described in the text.

Some of the current limitations on ground-motion simulations are related to the lack of details in the *USR*, such as inadequate spatial resolution of seismic wavespeeds. Hence, improvement of the *USR* by the *inversion* (*INV*) of observed ground motions constitutes another important computational pathway:

Pathway 4: $GM_{obs} \rightarrow INV \rightarrow USR$.

Computational solutions to the inverse problem require the ability to solve, often many times, the forward problems of Pathways 2 and 3. In particular, *INV* for seismic tomography can be constructed as *AWP†*, the adjoint of anelastic wave propagation, analogous to inversion and data-assimilation methods in oceanography and other fields [Tromp et al., 2006; Chen et al., 2007]. The SHA computational pathways are summarized in Figure 6.

The CME infrastructure currently includes three computational platforms. Each computational platform comprises the hardware, software, and expertise (wetware) needed to execute and manage the results from one or more of the SHA pathways of Figure 6. *OpenSHA* is a open-source, object-oriented, web-enabled platform developed in partnership with the USGS for executing a variety of Pathway-1 calculations, including the comparisons of hazard curves and maps from different PSHA models calculations, and for delivering physics-based (Pathway-1*) seismic hazard products to end users [Field et al., 2003, 2005].

TeraShake is a research platform for simulations of dynamic ruptures (Pathway 3) and ground motions (Pathway 2) on dense grids (outer/inner scale ratios > 10^3) [Cui et al., 2007]. TeraShake simulations show how the chain of sedimentary basins between San Bernardino and downtown Los Angeles form an effective waveguide that channels surface waves along the southern edge of the San Bernardino and San Gabriel Mountains [Olsen et al., 2006]. Earthquakes scenarios with northwestward rupture, in which the guided surface wave is efficiently excited, produce unusually high long-period ground motions over much of the greater Los Angeles region.

CyberShake is a production platform that employs workflow management tools [Deelman et al., 2006] to compute and store the large suites (>10^3) of ground motion simulations needed for physics-based PSHA (Pathway 1*). For each large ($m > 6.5$) source, the hypocenter, rupture rise-time and velocity distributions, and final slip distribution have been varied according to a pseudo-dynamic model, producing catalogs of more than 100,000 *KFR*s. Using receiver Green tensors and seismic reciprocity [Zhao et al., 2006], we have synthesized the ground motions at individual sites for the full suite of *KFR*s and, from this database, we have used OpenSHA to compute hazard curves for spectral accelerations below 0.5 Hz [Graves et al., 2006].

SCEC is now increasing the performance of these platforms to take advantage of the petascale computational facilities that will be developed by NSF during the next several years. This *PetaSHA* project has three main science thrusts: (1) Extend deterministic simulations of strong ground motions to 3 Hz for investigating the upper frequency limit of deterministic ground-motion prediction. (2) Improve the resolution of dynamic rupture simulations by an order of magnitude for investigating the effects of realistic friction laws, geologic heterogeneity, and near-fault stress states on seismic radiation. (3) Compute physics-based PSHA maps and validate them using seismic and paleoseismic data.

7. Communication, Education & Outreach

SCEC provides the public with useful knowledge for reducing earthquake risk through partnerships in science, engineering, risk management, government advisement, and education (Figure 3). The goals of its Communication, Education & Outreach (CEO) Program are to advance earthquake knowledge and science literacy at all educational levels; to improve earthquake hazard and risk assessments; and promote earthquake preparedness, mitigation, and planning.

The CEO Program offers a wide range of student research experiences, web-based education tools, classroom curricula, museum displays, public information brochures, online newsletters, and technical workshops and publications.

The Implementation Interface, a component of the CEO Program, integrates physics-based seismic hazard analysis into earthquake engineering research and practice through collaborations with Pacific Earthquake Engineering Research (PEER), the Consortium of Universities for Research in Earthquake Engineering (CUREE), and the Next Generation Attenuation (NGA) Project. It is developing an interface between SCEC and NSF's George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES).

CEO achievements include two successful intern programs, Undergraduate Studies in Earthquake Information Technology (UseIT) and Summer Undergraduate Research Experiences (SURE); the development of the Electronic Encyclopedia of Earthquakes as part of the NSF National Science Digital Library; the establishment of the Earthquake Country Alliance to present consistent earthquake information to the public; and new editions of the practical guide, *Putting Down Roots in Earthquake Country*, in both English and Spanish.

8. SCEC3 Science Plan

The science plan for next 5-year phase of the Center, SCEC3 (2007-2012), is articulated in terms of four basic science problems that organize the most pressing issues of earthquake system science.

- *Earthquake Source Physics*: to discover the physics of fault failure and dynamic rupture that will improve predictions of strong ground motions and the understanding of earthquake predictability.
- *Fault System Dynamics*: to develop representations of the postseismic and interseismic evolution of stress, strain, and rheology that can predict fault system behaviors.
- *Earthquake Forecasting and Predictability*: to improve earthquake forecasts by understanding the physical basis for earthquake predictability.
- *Ground Motion Prediction*: to predict the ground motions using realistic earthquake simulations at frequencies up to 10 Hz for sites in Southern California.

Table III.2 displays the priority science objectives developed as part of this plan.

The science plan also involves a number of special projects that will augment the basic research program (the pink boxes in Figure 4). Examples include the extension of the CME to a petascale cyberfacility (PetaSHA), the 2007 Working Group on California Earthquake Probabilities (WGCEP), and the new Collaboratory for the Study of Earthquake Predictability (CSEP). A real-time demonstration project in earthquake early warning has been initiated in partnership with the California Integrated Seismic Network and USGS. SCEC and the USGS are also promoting a Southern San Andreas Fault Evaluation (SoSAFE) project that will enhance the collection and interpretation of geologic and paleoseismic data on 2000 years of this important fault's slip history. In partnership with earthquake engineers, SCEC researchers are embedding built structures in geologic models to conduct end-to-end simulations ("rupture to rafters") of earthquake risks.

Table III.2. Priority Science Objectives for SCEC3

1. Improve the unified structural representation and employ it to develop system-level models for earthquake forecasting and ground motion prediction
2. Develop an extended earthquake rupture forecast to drive physics-based SHA
3. Define slip rate and earthquake history of southern San Andreas fault system for last 2000 years
4. Investigate implications of geodetic/geologic rate discrepancies
5. Develop a system-level deformation and stress-evolution model
6. Map seismicity and source parameters in relation to known faults
7. Develop a geodetic network processing system that will detect anomalous strain transients
8. Test of scientific prediction hypotheses against reference models to understand the physical basis of earthquake predictability
9. Determine the origin and evolution of on- and off-fault damage as a function of depth
10. Test hypotheses for dynamic fault weakening
11. Assess predictability of rupture extent and direction on major faults
12. Describe heterogeneities in the stress, strain, geometry, and material properties of fault zones and understand their origin and interactions by modeling ruptures and rupture sequences
13. Predict broadband ground motions for a comprehensive set of large scenario earthquakes
14. Develop kinematic rupture representations consistent with dynamic rupture models
15. Investigate bounds on the upper limit of ground motion
16. Develop high-frequency simulation methods and investigate the upper frequency limit of deterministic ground motion predictions
17. Validate earthquake simulations and verify simulation methodologies
18. Collaborate with earthquake engineers to develop rupture-to-rafters simulation capability for physics-based risk analysis
19. Prepare post-earthquake response

Additional information about SCEC and its programs can be found at http://www.scec.org.

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IV. Research Accomplishments

This section summaries the main research accomplishments and research-related activities organized by the disciplinary committees, focus groups, and special project working groups during SCEC2.

Geodesy

The SCEC2 geodesy program focussed on producing data, and analyses, of current crustal motion to aid in the understanding of earthquake physics in Southern California. Many of these results have rested on SCEC's willingness to support long-term and collaborative efforts.

The longest-running effort has been the the SCEC Crustal Motion Map, Version 3 of which was released in August 2003 (http://epicenter.usc.edu/cmm3). This included 833 estimates of current station velocities (relative to North America) at 762 points in Southern California and northern Baja California, together with coseismic offsets for the Landers earthquake (at 353 locations), Northridge earthquake (97 locations), and Hector Mine earthquake (250 locations). The velocities were derived from EDM data between 1973 and 1991, and GPS data from 1986 through 2001. This product has been used by a number of investigators to determine slip rates on faults throughout Southern California (Meade and Hager 2005, McCaffrey 2005, Becker *et al* 2005) and for other investigations (Fay and Humphreys 2005, Wdowinski *et al.* 2007). Work has continued on an improved version of this throughout SCEC2, in order to include additional data that became available; the new version (to be released in 2007) increases the number of GPS-based velocities by a factor of 1.3. Figure 7 shows Version 3 points (black) and those added (red).

During SCEC2 the SCIGN GPS array completed its construction phase and began full operation. One novel use of the array was to record large dynamic strains from a teleseismic event (the Denali earthquake) as these propagated through the Los Angeles basin. The SCIGN stations in Orange County were upgraded to 1-Hz sampling (using County funds); stacking of the relative displacements between stations of this network showed the seismic strains, at a distance greater than these had previously been recorded (Bock *et al.* 2004).

Joint analysis of InSAR and SCIGN data from the Los Angeles area provided new information about the deformations caused by groundwater pumping and withdrawal. For the SCEC mission of measuring fault-caused deformations in this important area they are a source of systematic error to be removed. The InSAR data show vertical motions, from which horizontal motions can be inferred; when these are applied to the SCIGN data, the pattern of deformation from faults in the Los Angeles basin is concentrated in the 20 km south of the San Gabriel mountains, as shown in Figure 8 (Argus *et al.* 2005). King *et al.* (2007) showed a large deformation response of this area to the heavy rains of winter 2004/2005.

Another InSAR result was the detection of slip on faults around the Hector Mine earthquake; Figure 9 shows the InSAR displacement field, highpassed to emphasize these local offsets. These offsets appear to have been caused by enhancement of the elastic response caused by a lower shear modulus in the fault zone; detailed analysis suggests a reduction in rigidity of a factor of two (Fialko *et al.* 2002). A similar change in rigidity, but on a larger scale, appears to be needed to explain the InSAR and GPS data around the Salton Trough (Fialko 2006).

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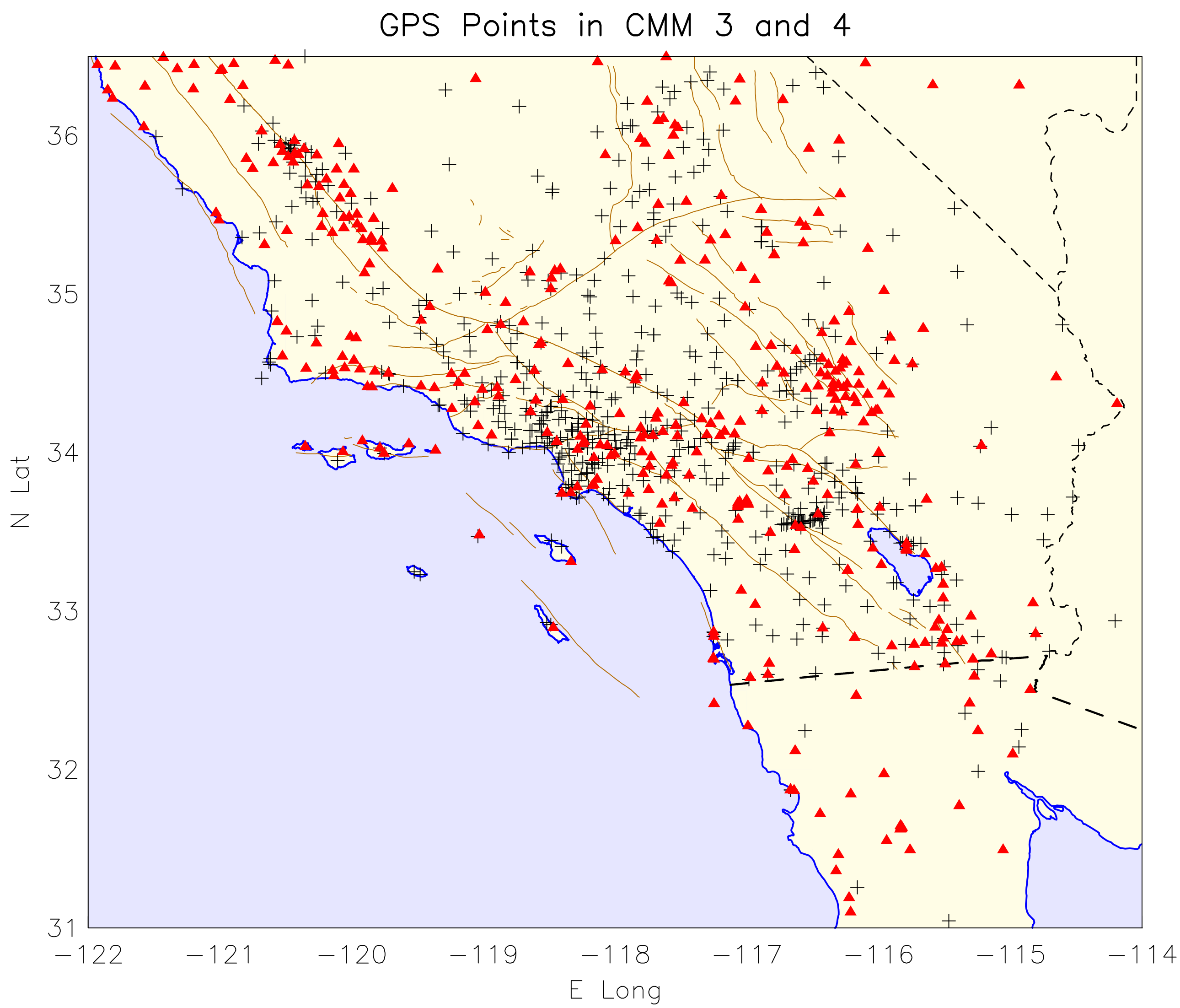
Figure 7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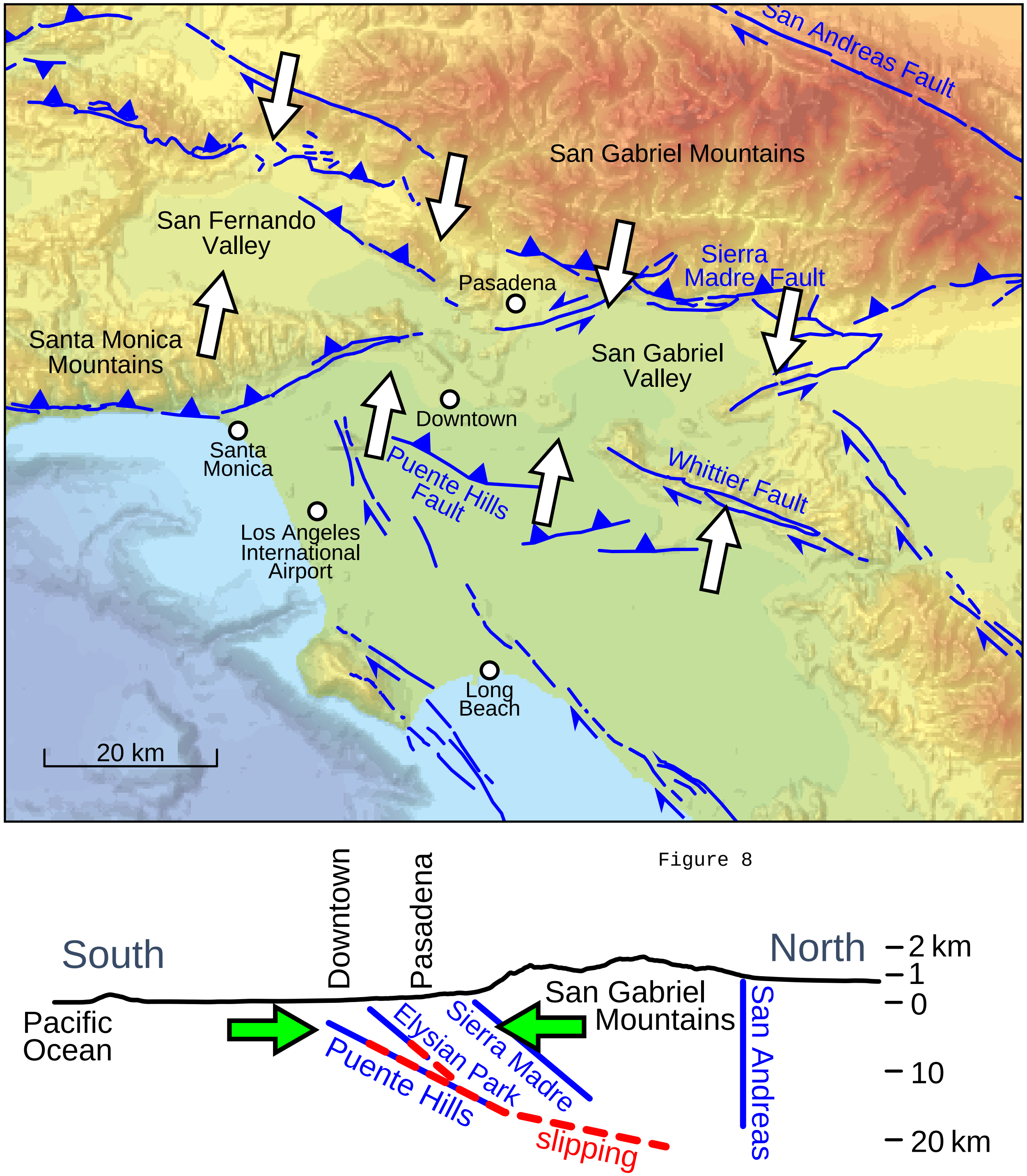
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Figure 8

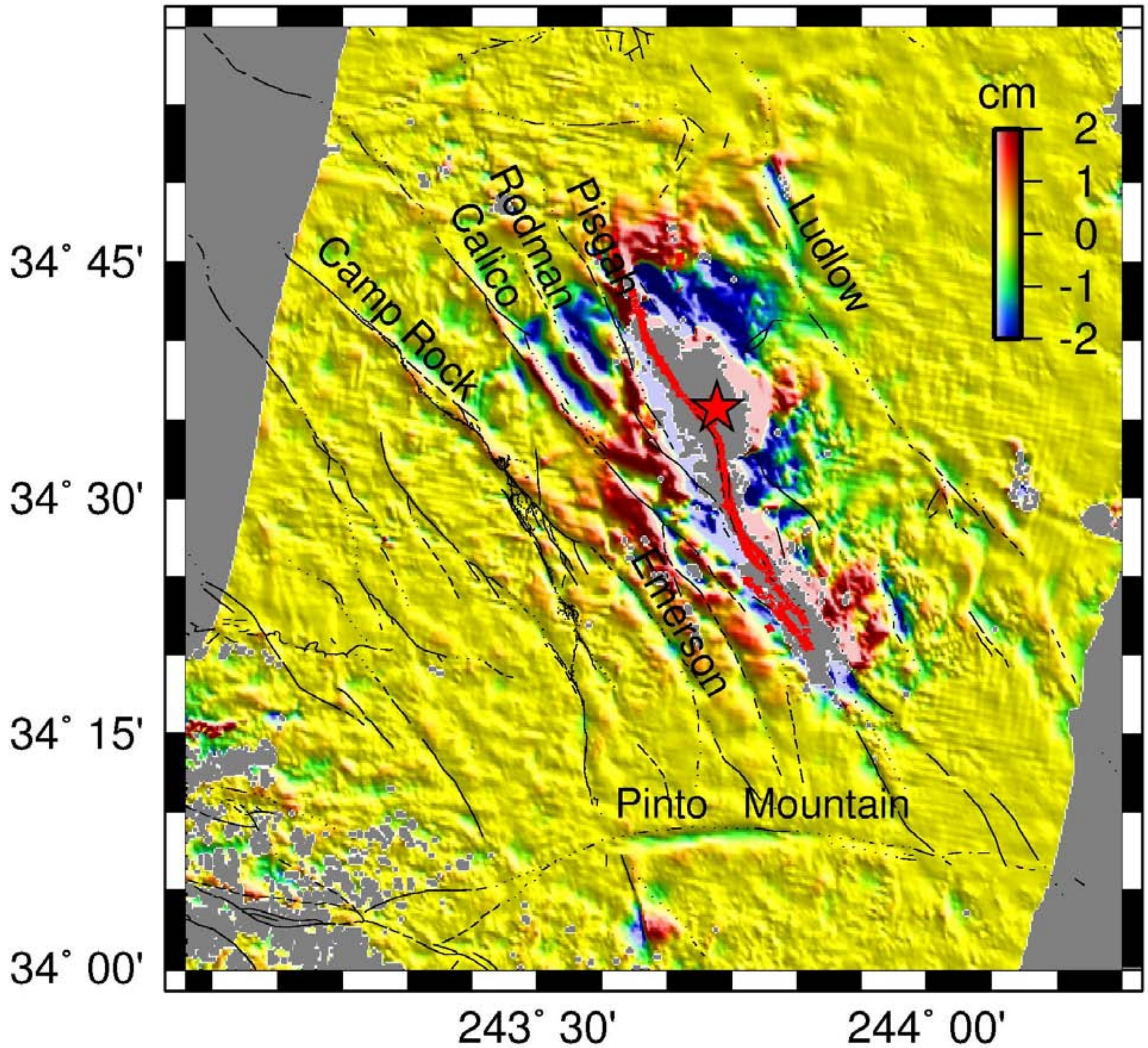
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Figure 9

Seismology

The Seismology Infrastructure focus group has funded 4-6 projects each year, emphasizing infrastructure and continuity. The mainstays have been: (1) the Southern California Earthquake Data Center, a Caltech/UCSD collaboration assembling earthquake catalogs and measuring earthquake properties and structure, (2) the Borehole Seismometer Network and the Portable Broadband Instrument Center managed from UC Santa Barbara, and (3) a short term SCEC2 contribution to the Strong Motion Database at UCSB.

Southern California Earthquake Data Center (SCEDC)

The primary resource for seismology research in southern California, the Southern California Earthquake Data Center archive as of 2006 had assembled 6 TB of waveform data (1981–present) and catalog information for 650,000 earthquakes (1932–present). On average, 1 waveform per second was distributed to the research community. The data center operates with its own advisory committee and is considered a model of service to science and society.

SCEC Borehole Program

This program, another mainstay of SCEC, maintains about 18 existing sites, with 7 installed toward the end of SCEC2, and takes advantage of cost sharing with other agencies to collaborate and support operations.

Portable Broadband Instrument Center

The PBIC currently is in maintenance mode, starting the transition to real-time telemetry. It can field a 20-station deployment, and is investigating ways to expand, collaborate, and modernize. A continuing stream of science experiments are being supported, the most current one is led by Elizabeth Cochran monitoring the Superstition Hills fault.

UCSD/Caltech waveform research

Peter Shearer and Egill Haukson are leading a multi-year effort to analyze the earthquake data at the SCEDC with new techniques. To facilitate this research, they have created an online waveform database for seismograms from 1981 to present. Projects have included: (1) A new 3-D crustal tomography model for southern California (*Lin et al.*, 2007), (2) earthquake relocations based on differential times obtained with waveform cross-correlation (*Hauksson and Shearer*, 2005; *Shearer et al.*, 2005; *Lin et al.* 2007), (3) a new *P* and *S* attenuation model for southern California (*Hauksson and Shearer*, 2006), and (4) comprehensive analysis of southern California *P*-wave spectra for earthquake source properties (*Shearer et al.*, 2006).

Figure 10 shows the improvements achieved in the new earthquake locations compared to the standard catalog for the Imperial Valley region. Notice the general sharpening of the seismicity features, which permits more detailed identification and mapping of fault structures. Just north of the Salton Sea, the new locations suggest that the San Andreas Fault dips at about 60 degrees to the northeast.

The *P*-wave spectral study used a method that isolated source, receiver and path dependent terms and applied a spatially varying empirical Green's function method. Estimated Brune-type stress drops for over 60,000 M_L = 1.5 to 3.1 earthquakes range from 0.2 to 20 MPa with no dependence on moment or local *b*-value. Median computed stress drop increases with depth in the upper crust, from about 0.6 MPa at the surface to about 2.2 MPa at 8 km, where it levels off and remains nearly constant in the mid-crust down to about 20 km. However, the results at shallow depths could also be explained as reduced rupture velocities near the surface rather than a change in stress drop. Spatially coherent variations in median stress drop are observed (see Figure 11), with generally low values for the Imperial Valley and Northridge aftershocks and higher values for the eastern Transverse ranges and the north end of the San Jacinto fault. No correlation is observed between stress drop and distance from the San Andreas and other major faults.

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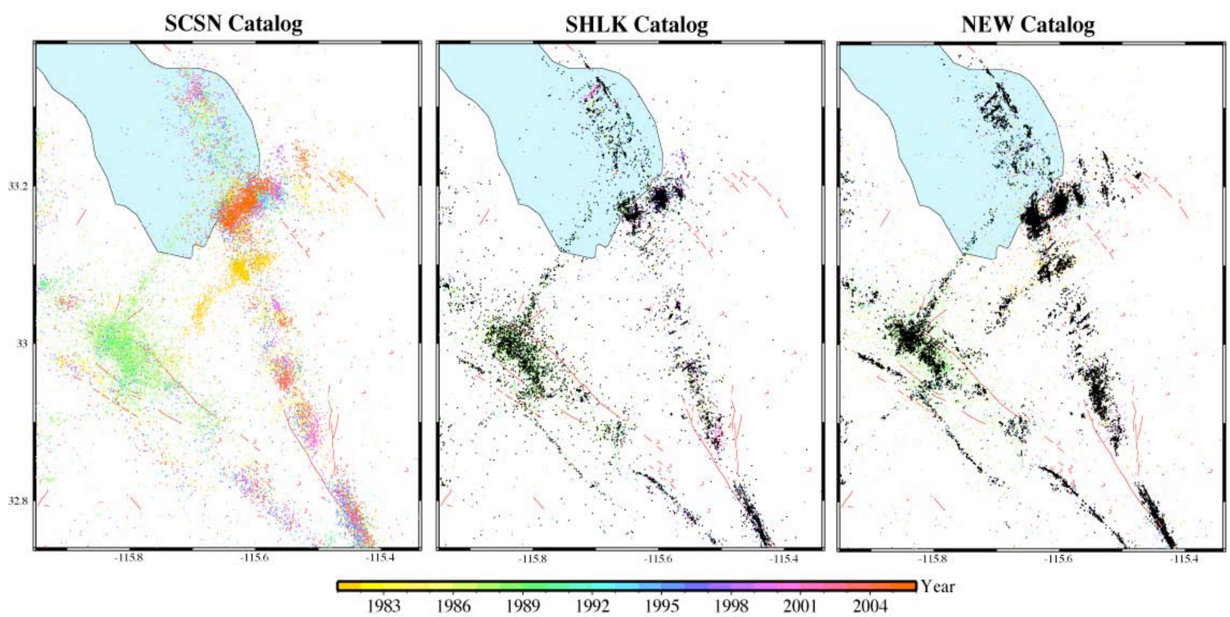

Figure 10. A comparison near the Salton Sea among earthquake locations from the standard SCSN catalog, the SHLK catalog (Shearer et al, 2005) and the new LSH catalog (Lin et al., 2007). Events within similar-event clusters that have been relocated by using waveform cross-correlation are shown in black. Events in the SCSN catalog (and uncorrelated events in the other catalogs are colored by their year of occurrence).

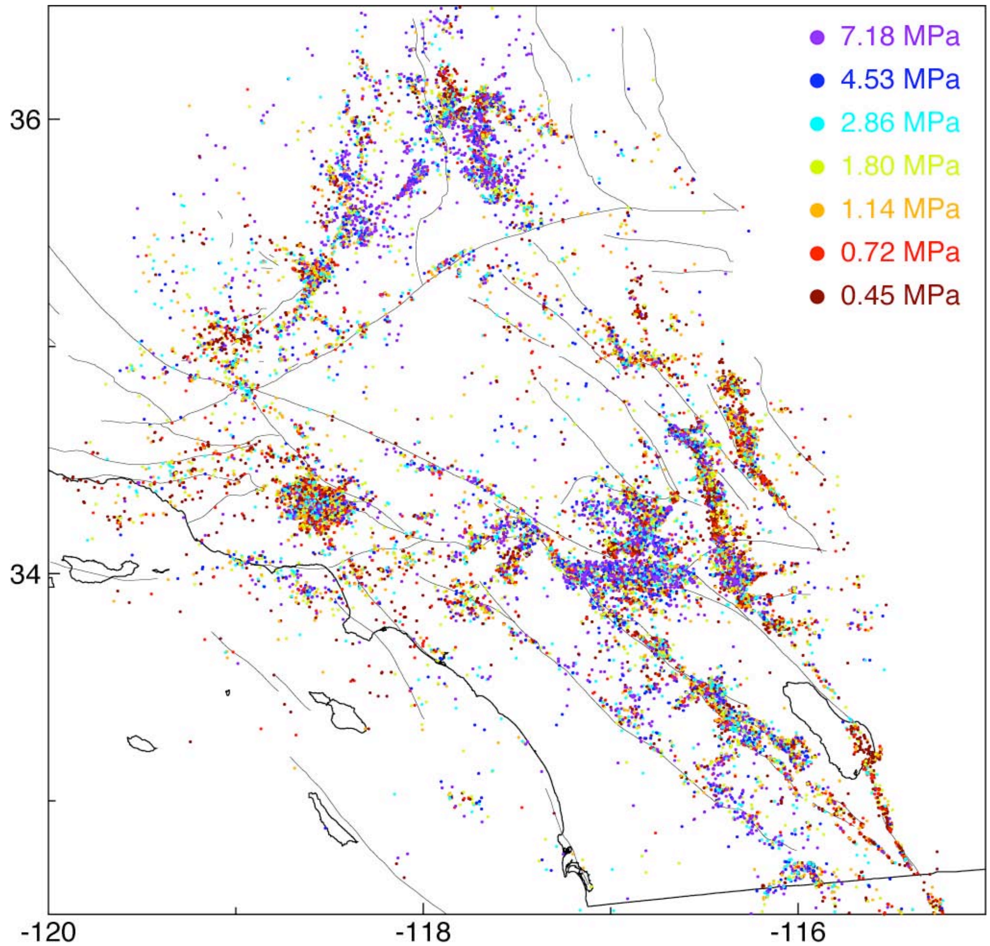

Figure 11. Estimated Brune-type stress drops for over 65,000 southern California earthquakes from 1989 to 2001. Results are colored in equal increments of log stress drop.

Geology

The geology disciplinary group coordinates a diverse research agenda drawing from the geologic record of southern California's natural laboratory. Though important advances were made in characterizing fault activity, notably on blind-thrust systems beneath the Los Angeles urban region (Sorlien et al., 2006, Dolan et al., 2003, Figure 12), much of the SCEC2 geology effort was closely linked with the focus group objectives. In addition, the geology disciplinary group also promoted efforts to acquire deep paleoseismic records, to compile community data sets, and to develop new quantitative methodology in earthquake geology.

Many geological investigations were collaborative with the focus groups. For example, the geology community contributed its collective knowledge and sometimes contentious debate to development of the community fault model – a component of the unified structural representation and one of the landmark achievements of SCEC2 (Plesch et al., 2002). The fault systems focus group also drew a variety of groundbreaking geologic research. New, deep paleoseismic time-series from the San Jacinto and San Andreas fault highlight clustering of earthquakes on these major plate boundary structures (Weldon et al., 2004; Rockwell et al., 2006). Compilation of the vast body of paleoseismic data available in southern California further highlights regional temporal clustering of earthquake activity, and suggests that there may be coherent patterns of activity related to time-dependent loading of faults (Dolan et al., in press; Figure 13). SCEC2-sponsored research also documented significant differences between geologic fault slip rates and geodetic fault loading rates in eastern California (Oskin and Iriondo, 2004) and on the southern San Andreas fault that could be linked to earthquake clustering phenomena. Other collaborative efforts combined mechanical modeling to test alternative models of fault geometry (Meigs et al., in press), compilation of precarious rock data as long-term strong ground-motion sensors (e.g., Brune, 2002), and investigations of fault-zone damage to refine understanding of the earthquake energy budget (Wilson et al., 2005; Chester et al., 2005) and test for preferred earthquake rupture direction (Dor et al., 2006).

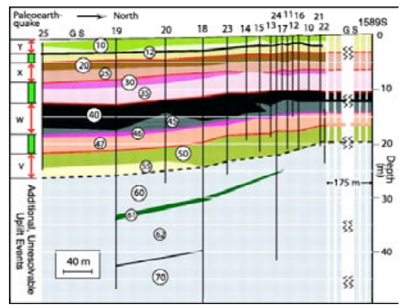

Figure 12. Thickening of strata across fold updip of the Puente Hills blind thrust indicates at least four large earthquakes in the past 11,000 years (Dolan et al., 2003).

SCEC2 also invested in improvements in the basic methodology of collecting and presenting earthquake geology data. A long-standing problem in paleoseismology has been the collection of "meta-data", that is, the detailed description of geologic relationships in trench exposures that allow interpretation of past

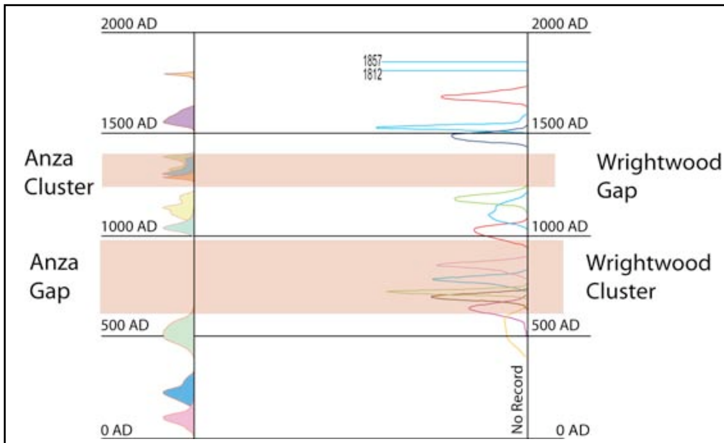

Figure 13. Comparison of earthquake activity from the San Jacinto fault, at Anza, to the San Andreas fault, at Wrightwood, suggests that clusters of activity on one fault occur while the other is quiescent (Rockwell, unpublished data).

surface ruptures. Along with chronologic efforts, these studies have led to the mining of the past large earthquake history in southern California which is used to place constraints on rupture models and earthquake forecasting. Inherent in this approach is that the "logs" themselves have a component of interpretation that may inject biases into the final results. Towards a more complete and less interpretive documentation of the past earthquake record, Ragona et al. (2006) developed new methodology to apply hyperspectral imaging of geologic exposures that accurately collect and archive the properties of the sediments or rock in that exposure. The ability to archive raw and processed data will make future re-interpretation much more productive and less subjective. SCEC2 also sponsored new research directions to advantage of another emerging technology: high-resolution LiDAR topography (Frankel and Dolan, 2007; Oskin et al., submitted). The well-exposed southern California natural laboratory provides an ideal test bed to explore the limits of how these new data illuminate of fault-zone history and processes.

The geology disciplinary group also promoted a number of studies to enhance quantitative representation and interpretation of earthquake geology data. In the area of seismic hazard analysis, SCEC2 sponsored continued development of Bayesian approach to paleoearthquake correlation (Biasi et al. 2002) that builds alternative rupture scenarios from variable-length paleoseismic records. Such scenarios form the basis for next-generation seismic hazard analyses. The Bayesian approach identifies multiple potential rupture scenarios for the San Andreas fault, from as few as 14, well-correlated earthquakes to over twice as many, smaller events with commensurably less correlation from site to site. SCEC2-sponsored research to compile historic earthquake ruptures also led to important new insights into fault segmentation and barriers to rupture propagation on strike-slip faults (Wesnousky, 2006). SCEC geologists also contributed to development of online community databases of fault activity and long-term vertical motions. These databases provide important context for interpretation of geodetic data in southern California.

Under SCEC2, the role of the geology disciplinary group within the center broadened significantly. Simultaneously, the research group has gained important cohesion necessary to tackle more ambitions projects in the future. One example of this community approach is the shared geochronology infrastructure system developed under SCEC2. This new approach to dating needs decreases costs and greatly increases flexibility for SCEC geologists to obtain critical dating support in a timely manner. Future collaborative efforts, such as the southern San Andreas fault initiative under SCEC3, will benefit significantly from what the geology community forged under SCEC2.

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Fault and Rock Mechanics

Fault and Rock Mechanics (FARM) was formed as a new disciplinary committee in SCEC2. The FARM initiative brought into SCEC a new community of scientists concerned with laboratory rock mechanics experiments, field studies of exhumed fault zones, and theoretical modeling of friction processes and fault mechanics. The participants collaborated productively, and consequently, as is illustrated below, made significant progress toward one of the central goals of SCEC, an understanding of what may occur on a fault zone during dynamic earthquake rupture.

The collaboration was advanced by five workshops, one each year of SCEC2.The first brought the group together to initiate interactions and outline the important issues that FARM could most effectively address. The second focused on one of those, namely the idea of using more realistic friction constitutive laws than slip weakening in dynamic rupture models. The third brought together the experimental rock mechanics community to outline and consider solutions to the scientific, demographic, and technical problems facing the community. The fourth and fifth were field-excursion-focused workshops that allowed participants with field, laboratory experimental, and theoretical expertise to discuss the behavior of faults while examining the evidence left by the faulting processes. The first of these unveiled a new SCEC guidebook (Evans and Chester, 2007, in preparation) to known exposures of exhumed faults while looking at several of them, especially the Punchbowl fault that shows 44 km of slip localized on a zone in which the majority of slip occurred across an ~1 mm thick zone. The second field-based workshop focused on the occurrence, and significance for stress during earthquakes, of pulverized rock found adjacent to the San Andreas and other faults in Southern California.

In order to reach the principal FARM goal, namely to construct and verify a model of fault-zone mechanics applicable to the nucleation, propagation, and arrest of dynamic rupture, it is important to understand the geometry and kinematics of fault zones, especially the distribution of slip across them as well as the interactions that occur in fault networks and within the surrounding material. Present FARM scientists are responsible via their previous work for our current understanding of the very localized slip that frequently occurs during faulting (Chester and Chester, 1998; Chester et al., 1993a, 1993b, 2004a; Chester and Logan, 1986, 1987; Schulz and Evans, 1998, 2000) and during SCEC2 have turned their attention to characterizing the distribution of damage and consequent energy dissipation in the form of creating interfacial energy from the ultacataclasite core to the undamaged country rock (Wilson et al., 2003; Chester et al., 2004b, 2004c, 2005). The localized character of the deformation at the Punchbowl fault is shown in Figure 14 and evidence for the distribution of damage across the fault zone is shown in Figure 15. The new studies of the fracture density and particle size distributions (Chester et al., 2004b, 2004c, 2005) show a dramatic grain-size reduction in the fault core, implying that the 300-mm thick ultracataclasite layer has as much surface area as all of the minor faults and microfractures in the entire 200 m wide damage zone. In spite of this large surface area, the surface energy it represents is only 10^4 to 10^5 J/m^2 of the fault surface per earthquake, about 100 times smaller than the typical fracture energy seismologically inferred for large earthquakes.

The field evidence for extremely localized deformation, at least at depths of about 3 km from which most of the exposures have been exhumed, is important in guiding both laboratory experimental and theoretical studies of fault friction and have implications for nucleation, rupture and arrest of dynamic slip. The extreme localization simplifies both experimental studies and theoretical models of dynamic weakening due to thermal pressurization of pore fluids. Furthermore, very localized slip makes it more likely that an important dynamic weakening mechanism could be “flash” heating, namely local heating, weakening and perhaps even melting at asperity contacts. A simple theory describing the consequences of this mechanism was presented by Rice (1999) and during SCEC2 was modified by Beeler and Tullis (2003) and

Beeler et al. (2007). This mechanism has been investigated in the laboratory by Goldsby and Tullis (2003). Weakening is seen for many rock types, and is illustrated for novaculite in Figure 3. Dramatic weakening is seen above slip velocities of 100 mm/s, just as predicted by the theory. Other experiments are underway to verify that the weakening shown in Figure 16 is in fact due to flash weakening. Pilot experiments supported entirely by SCEC that have been conducted by Prakash and Yuen (2005), using experimental methods new to geophysics, also show low friction consistent with flash weakening as shown in Figures 17 and 18. The experimental techniques used to generate these data are illustrated in Figures 19 and 20.

A theoretical study of dynamic rupture, that illustrates how the field and laboratory data can be used to discover new behavior that may occur during earthquakes, has been conducted by Lapusta and Rice (2004a, 2004b). In this study, instead of simply using slip-weakening friction as has been done in many other studies, they used frictional weakening due to the combination of two processes, thermal pressurization and flash heating. The theoretical basis for the weakening due to thermal fluid pressurization was provided by Rice (2003, 2005). The combination of initial weakening due to flash heating and continued weakening due to thermal fluid pressurization results in dynamic friction coefficients that are much lower than the quasi-static values of ~0.6-0.8. Although the model can be run with a variety of initial stress states, one of the interesting possibilities with the Lapusta and Rice model is that a series of earthquakes can occur with an average stress that is quite low. This is possible because, once a rupture is initiated in a nucleation area where the high static frictional strength of the fault is overcome by either high local stress or low static strength, the static friction along the rest of the fault is overcome by the dynamic stress concentration at the tip of the propagating rupture. This behavior is illustrated in Figure 21. One of the important features of such a model is that because slip occurs at low stresses, the heat generation is low and satisfies the observed low heat flow constraint (Lachenbruch and Sass, 1980).

Although space prohibits describing more examples, the interactions between field, and theoretical studies illustrated above show the synergistic collaboration that FARM has added to SCEC during SCEC2. It is notable that the information flow goes in all directions. Thus, it is not just that the observations of narrow slip zones and low observed friction provide a framework for theoretical models. The theoretical importance of localized slip zones push field observers to continue to determine how universal is the localization of slip. Theoretical studies of expected stresses adjacent to propagating ruptures have led field observers to look for fracture orientations and distributions that are predicted and that might demonstrate a preferred direction of dynamic ruptures. Theoretical and laboratory studies inform each other, so that experiments check theoretical predictions and theoretical models use experimental data. Laboratory and field studies go hand-in-hand, since the same deformation processes can occur in both settings, and the deformation features are therefore related. Laboratory tests can determine what rheological behavior is associated with each process, and field study can tell us which processes operate on faults. Under the umbrella of the FARM disciplinary committee during SCEC2, all of these interactions have flourished.

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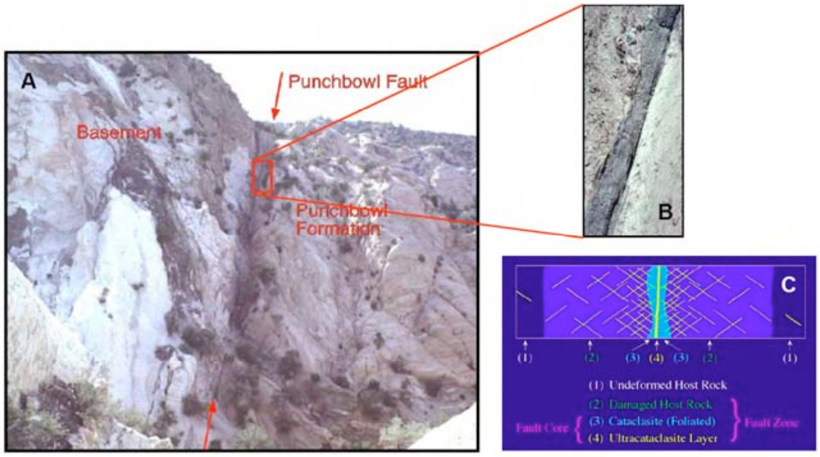


Figure 14. *Panel A***:** In the Devil's Punchbowl area, the Punchbowl fault juxtaposes igneous and metamorphic rocks of the San Gabriel basement complex and arkosic sedimentary rocks of the Punchbowl Formation. The fault is a 100 m thick zone of fractured and folded rock bounding a meters thick, narrow zone of high shear strain. The two protoliths are juxtaposed along single, continuous layer of ultracataclasite within high shear zone. *Panel B***:** The ultracataclasite is distinct and forms sharp contacts with the bounding cataclasites. Deformation is dominantly brittle, though evidence exists for alteration, neomineralization, and some pressure solution. *Panel C:* Conceptual model of a typical large displacement fault (Chester and Chester, 1998; Chester et al., 1993; Chester and Logan, 1986; Chester and Logan, 1987)[*Chester et al*., 2005]. The very localized slip provides valuable input to theoretical models of dynamic rupture on faults.

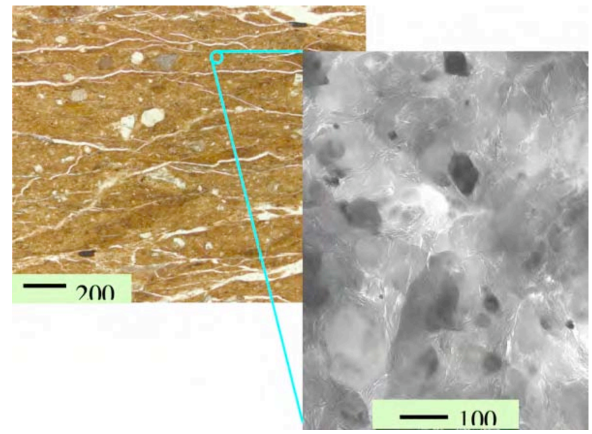


Figure 15. TEM imaging of an ultracataclasite from the Punchbowl fault core documents showing that most particles are less than 100 nanometers in diameter. These small particles are of host rock mineralogy and thus formed through cataclastic grain size reduction. Consequently the grain boundaries of these small particles constitute fracture surface area. Scale bar in optical photo at left is in mm, on TEM photo at right is in nm. (Chester, et al., 2005).

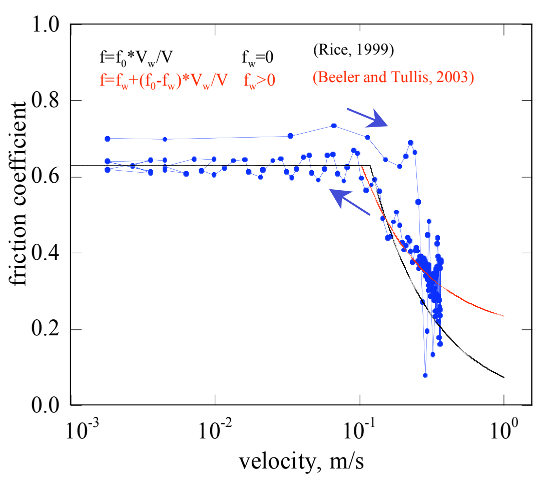


Figure 16. Data showing 'flash' weakening, plotted as friction vs. velocity. Arrows show time sequence of data. Smooth black and red lines show predictions of theory of Rice (1999) and of Beeler and Tullis (2003) and Beeler et al. (2007), respectively.

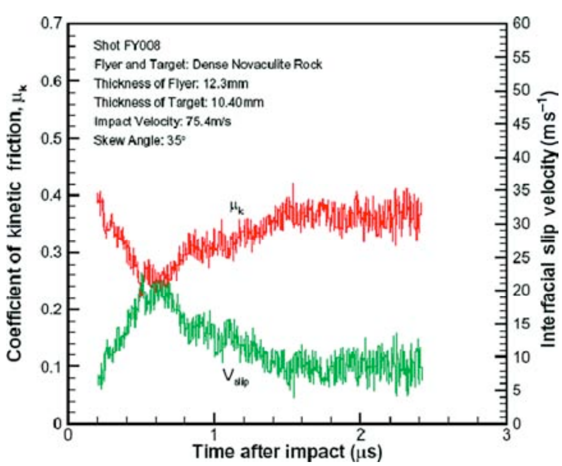


Figure 17. Friction (red) and slip velocity (green) vs. time for pressure shear experiment on novaculite (Prakash and Yuan, 2004).

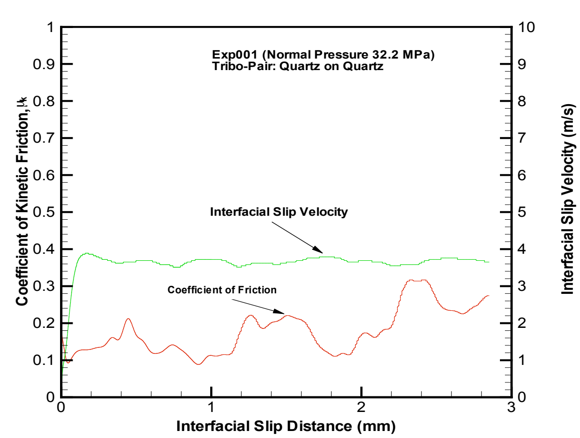
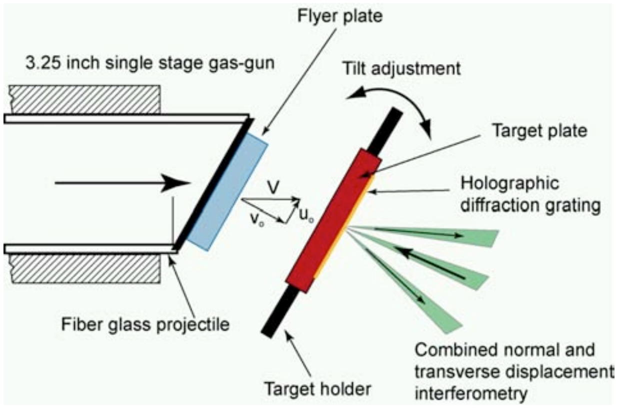


Figure 18. Friction and slip velocity for torsional Kolsky bar experiment on novaculite (Prakash and Yuan, 2004).



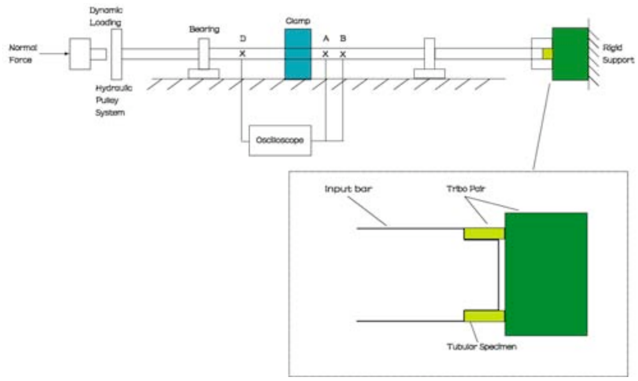


Figure 19. Plate impact pressure shear friction experiment. Normal stresses can range from 100 to 2000 MPa, slip speeds from 1 to 50 m/s, and slip up to 0.5 mm.

Figure 20. Torsional Kolsky bar friction experiment. Normal stresses can range from 1 to 100 MPa, slip speeds from 1 to 10 m/s, and slip up to 10 mm.

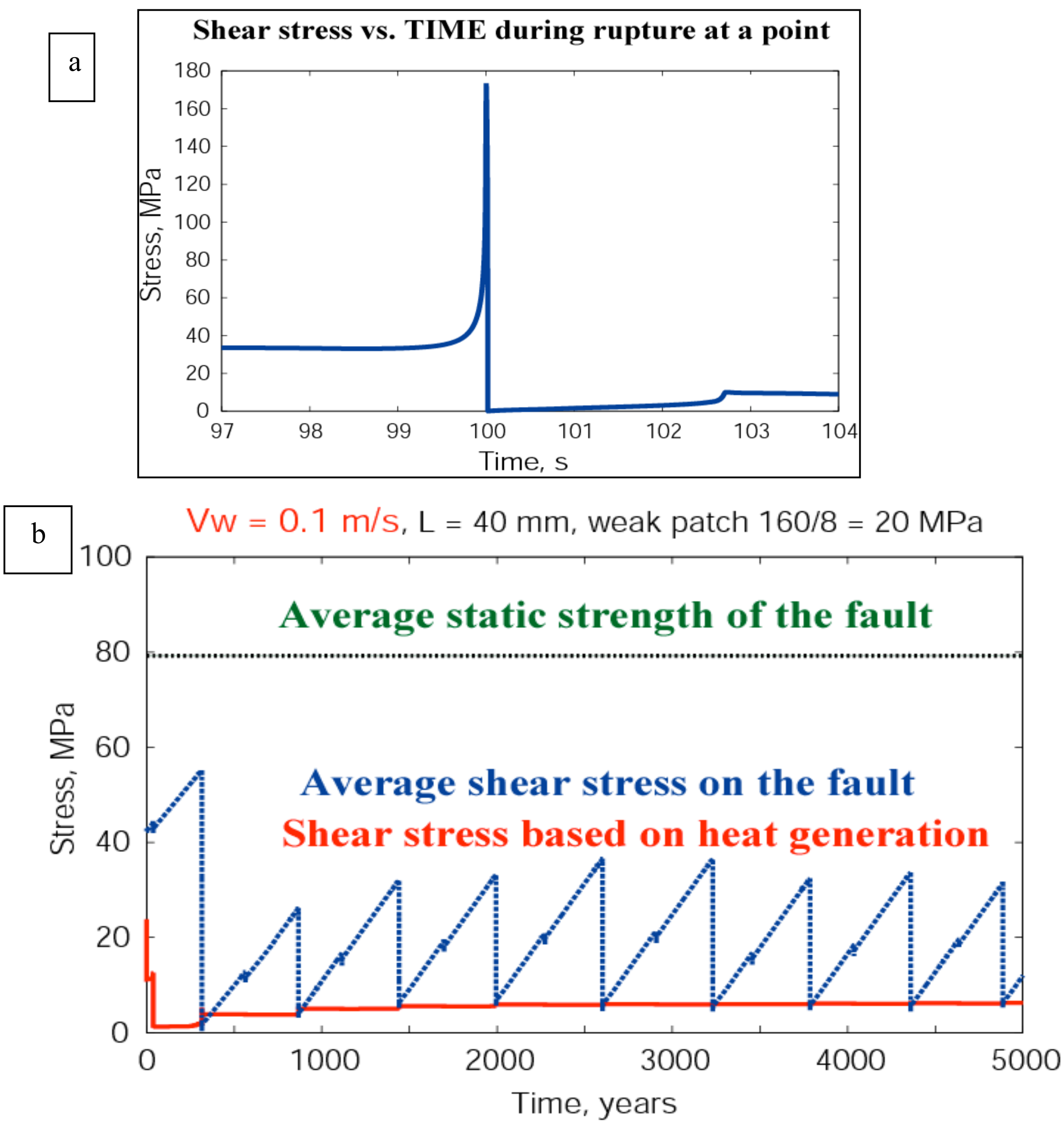


Figure 21. a. Stress variation in a 2D dynamic rupture for which rate and state friction with strong dynamic weakening is used (*Lapusta and Rice*, 2004a, 2004b). The diagram can also be thought of as essentially showing the stresses around the tip of a rupture propagating to the left and located at the 100s mark. The tectonic stress level at the left is much lower than the static strength which is overcome by the dynamic stress concentration. After the rupture passes sliding occurs at essentially zero strength and then recovers when the slip velocity drops and the rupture heals. **b.** In a series of dynamic ruptures similar to that shown in **a** the average shear stress on the fault oscillates, but never reaches the static strength. Because most of the slip all occurs at a low stress level, due to the velocity and displacement dependent friction, heat generation is low and would satisfy the observed heat flow constraint (*Lachenbruch and Sass*, 1980).

Earthquake Source Physics

The goal of the Earthquake Source Physics focus group has been to understand the physics of earthquake rupture nucleation, propagation, and termination and the resulting generation of strong ground motion.

A 5-year overview of SCEC2 Earthquake Source Physics demonstrates both exciting leaps of scientific progress and topics that still, in 2007, need further investigation. We started ESP with the basic idea that it would be good to include the earth's observed complexity in our understandings of earthquake mechanics and ground motions, but it has taken awhile to implement this difficult goal. For example, we started ESP with the vision that there would be a seamless overlap between coseismic and interseismic fault simulations using reasonable friction laws, but it was just at the end of SCEC2 that this was realized, with PI Lapusta simulating full-cycle sequences of earthquakes. Another challenge of ESP and SCEC2-FARM and now moving into SCEC3 is that we still need to pin down the real mechanical processes that operate both on and off-fault during earthquakes. In SCEC2, ESP, along with FARM, started by concentrating on understanding coseismic weakening, generally using slip-weakening in coseismic rupture simulations. Although by the end of SCEC2, numerous alternative processes have been presented based on laboratory experiments, there is still not one process that stands out, and of the range of processes, few have been rigorously tested against ground motion observations. Therefore investigations into the nature of fault friction will remain an essential topic of investigation in SCEC3.

One achievement for ESP is that we now have the capability of testing and comparing the various methods that we use to computationally simulate spontaneous earthquake rupture propagation. The SCEC Rupture Dynamics Code Validation Exercise is fully operational (and extending into SCEC3) and has helped numerous ESP (and Ground Motions) investigators check their codes and fix them when appropriate. This congenial collaborative SCEC exercise started out with simple vertical strike-slip fault rupture, and simple slip-weakening in SCEC2, and in SCEC3 is venturing into dip-slip faulting and other frictional forms.

Another achievement of ESP is a new view of the importance of off-fault faulting and damage on the energy budget and ground motions of earthquakes. This topic, barely if at all discussed in SCEC1, leaped to the forefront in SCEC2 and remains a topic of much interest in SCEC3. It is thought that a solution will help us better predict extreme ground motions (e.g. the DOE Extreme Ground Motions project), and the state of stress on faults.

On a related note, the effects of the heterogeneity of stress, geometry, and fault-abutting materials have been widely tackled in ESP during SCEC2, using both observational and numerical viewpoints. The correct forms of stress and strength heterogeneity, fault stepovers and bends, and bimaterials with and without pore-fluids were all topics of interest and publications. It is likely that none of these factors can be ignored in realistic earthquake simulations, since each individual SCEC2 study showed a significant effect of including these complexities. An exciting development in SCEC2 was some of the first collaborative laboratory/numerical simulations of dynamic rupture (on a material other than foam-rubber) that occurred in the Rosakis lab at Caltech. Comparisons with work of the Rice group and the

Sammis group show much promise and this seems an ideal path to continue in SCEC3 (Figure 22).

On the observational ESP front, an M6 Parkfield earthquake (Figure 23) shook up some of our expectations about earthquake predictability, and also reaffirmed other ideas (for an overview, please see Harris and Arrowsmith, Bull. Seism. Soc. Am., volume 96, issue 4b, 2006). For example, the 2004 Parkfield earthquake helped sink the unilateral rupture propagation idea based on material contrasts, a long-term debate within the SCEC community. On the other hand, Parkfield reaffirmed studies of ground motion variability, and off-fault damage, and how the earthquake source contributes to it. With SCEC2 partial funding, a highly successful source model database was compiled by Martin Mai. This database can now be used to compare earthquake rupture models and ground motions.

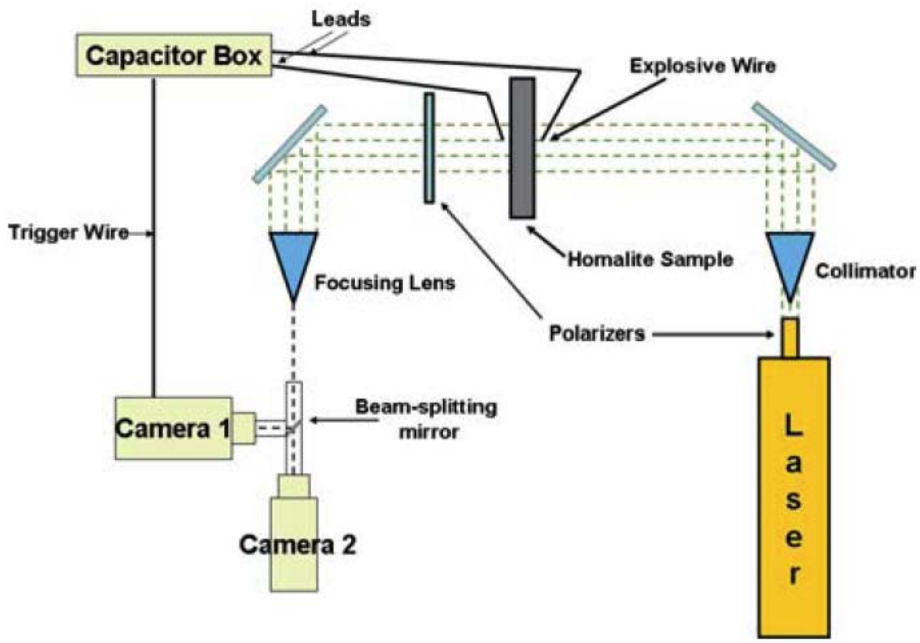
Observations of small, moderate, and large earthquakes were used by SCEC2 ESP researchers to study if the physical processes of small and large earthquakes are the same. ESP researcher McGuire showed similar rupture velocities of small and large events, and ESP PI's Rice and Abercrombie showed that small and large earthquakes appear to behave similarly in terms of energy consumption and release.

Whereas the previously mentioned research delved into aspects of earthquake scaling, the earthquakes themselves, namely relocations of small earthquakes contributed to a fantastic new view of southern California's faults at depth, with work by ESP PI's Shearer and Hauksson. This new catalog shows the range of structures that need to be included in SCEC3 efforts such as WGCEP, and also are an indication of the fault geometries that need to be included in earthquake source physics and fault systems simulations.

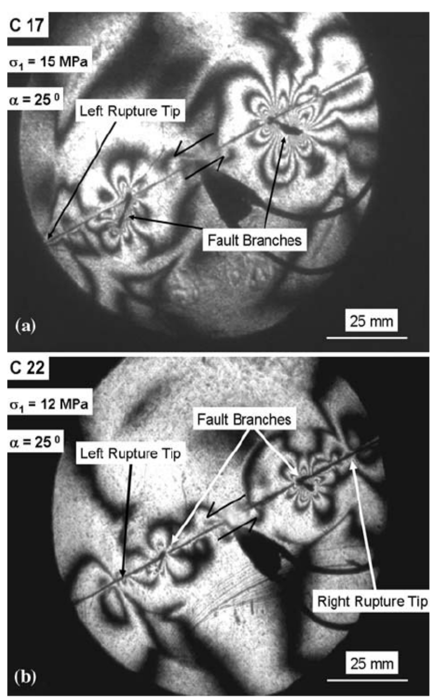
In SCEC2, observations of southern California aftershocks by ESP PI's Vidale, Peng, and Beroza led to a better understanding of small-aftershock triggering that was previously undetected in the coda of mainshocks. The inclusion of these early aftershocks help pin down the appropriate relationships between mainshocks and their aftershocks. On a related note, questions of earthquake triggering were kept alive in SCEC2, with a voice appealing to dynamic triggering as the dominant mechanism, compared to static stress triggering. Perhaps in SCEC3 we will finally solve this problem.

At the beginning of SCEC2, there were two groups targeting earthquake and fault mechanics problems with overlap, yet sometimes not sufficient collaboration. An early SCEC2 effort by FARM leader Terry Tullis brought FARM to the forefront of SCEC2 minds, then brought the FARM and ESP groups together, with two successful joint FARM/ESP workshops. The understanding by ESP and FARM leadership that the two groups are synonymous, at least from the fault mechanics viewpoint, has led to the creation of a unified Fault and Rupture Mechanics group in SCEC3.

Figure 22

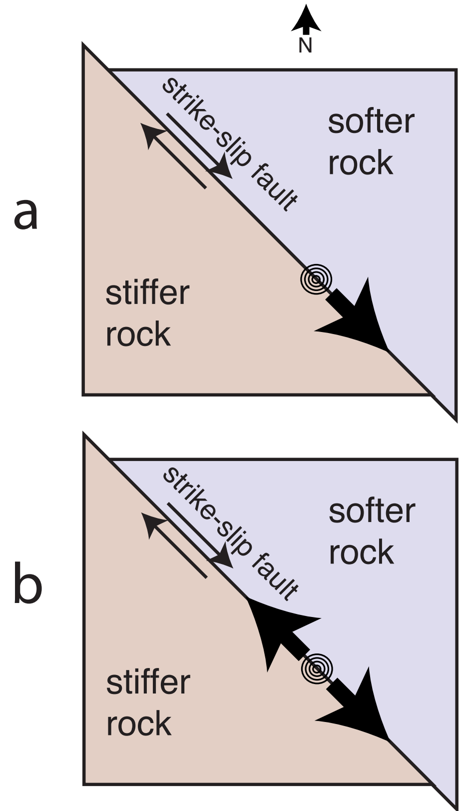


Biegel, R., and C. Sammis, Pure and Appl. Geophys., 2007.
Diagram of the experimental apparatus used to observe dynamic rupture interaction with fault branches.

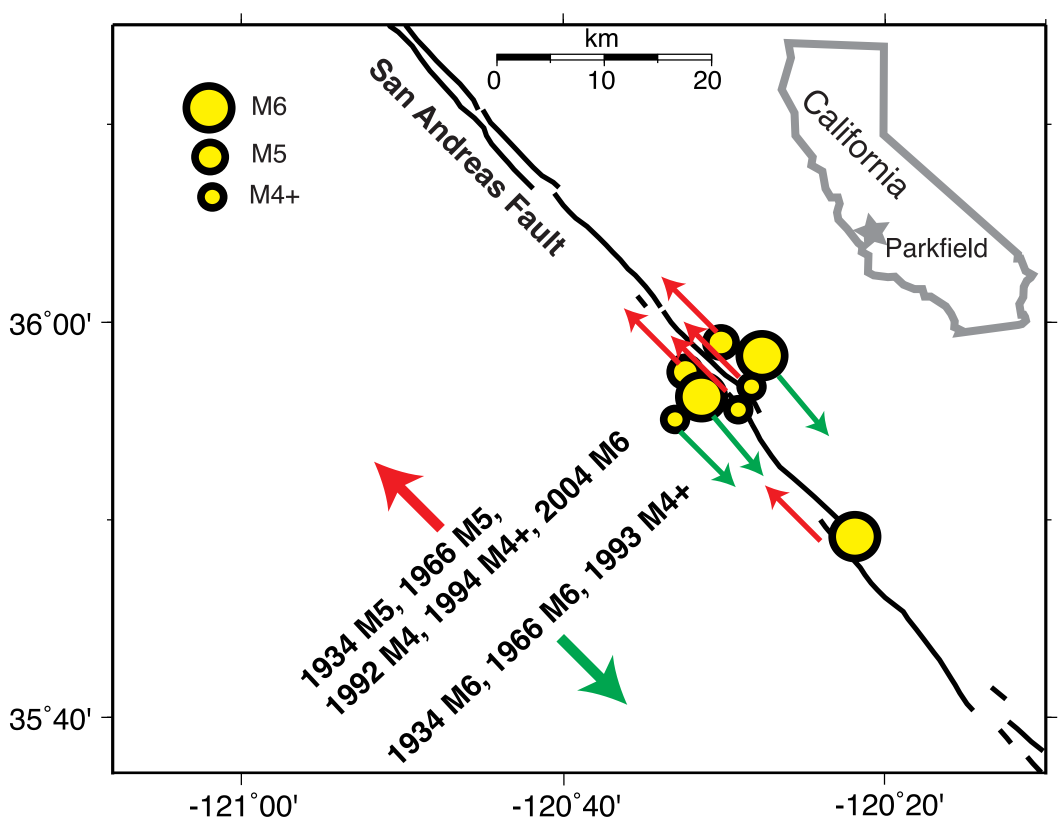


Biegel, R., and C. Sammis, Pure and Appl. Geophys., 2007.
a) Image from experiment C-17 on homalite sample. The left rupture tip passed the left branch and went supershear (Mach cone), but the right tip cannot be seen because it was stopped by the right branch.
b) Image from experiment C-22. Both rupture tips passed their respective fault branches.

Figure 23



Harris and Day, Geophys. Res. Lett., 2005
Effect of a material contrast on a dynamic rupture. a) In the preferred direction hypothesis rupture is unilateral and in the direction of slip of the softer rock. b) In the non-preferred direction hypothesis rupture is bilateral.



Harris, R.A. and S.M. Day, Geophys. Res. Lett., 2005
Parkfield earthquakes show a range of propagation directions (arrows) and indicate that material contrast does not lead to a preferential rupture propagation direction.

Fault Systems

Two overarching questions asked by the Fault Systems Working Group (FSWG) are: 1) What are the spatial variation and temporal evolution of stress in the southern California fault system and how does this evolving stress state relate to earthquake probabilities? and 2) What are the spatial variations in deformation and how does deformation evolve on temporal scales relevant to geology (10^5 – 10^6 yrs), paleoseismology (10^3-10^5 yrs), the earthquake cycle (10^0 – 10^3 yrs) and earthquake rupture initiation (10^{-5} – 10^0 yrs). We seek to understand the kinematics and dynamics of the southern California fault system on earthquake-initiation to geologic time scales and to apply this understanding to constructing probabilities of earthquake, including time-dependent earthquake forecasting. Two broad approaches are followed, both rooted in model-based inference: 1) Quantitative comparisons of observations to predictions of models of ongoing crustal deformation and stress evolution, and 2) A systems level approach characterizing and understanding spatial and temporal patterns in regional seismicity, with the ultimate objective of intermediate-term earthquake prediction. The scope of the effort is broad and the FSWG has strong ties to the Unified Structural Representation, Earthquake Source Physics, FARM, and RELM Working Groups, and is dependent on observations provided by Earthquake Geology and Tectonic Geodesy. In this brief summary, we focus on research themes that were enabled by and contributed to the systems approach fostered by SCEC2.

Fault System Geometry: The interaction of faults in the 3-D, geometrically complex fault system of southern California is a research theme that cuts across all these time scales. The basic geometry (CFM) has been developed by the USR group headed by John Shaw, with the CBM resulting from collaboration with the FSWG. A number of FSWG researchers (Jim Dieterich, John Rundle, Steve Ward, Terry Tullis) have developed earthquake simulators that address at varying spatial scales the effects of fault system geometry on seismicity. The nonlinear interactions resulting from fault system geometry alone explain some of the variability seen via paleoseismology, while variations in fault properties such as those determined by the FARMers are also important (Fig. 24). Complexities from fault system geometry and structure also lead to heterogeneity in stress (Tom Heaton) and strain (Thorsten Becker) inferred from earthquake focal mechanisms.

FSWG (e.g., Peter Bird, Brendan Meade, and Brad Hager) has shown that geometric complexity also has a major influence on the inference of fault slip rates from the geodetic observations of the Tectonic Geodesy Working Group. Major conclusions (Fig. 25) are that the slip rate on the San Bernardino segment of the San Andreas fault is much lower than previous geologic estimates and that the total slip rate across the Mojave region of the ECSZ is much greater than previously found via geologic studies. This apparent conflict led SCEC2 geologists (e.g., Sally McGill and Mike Oskin) to focus on the regions of disagreement. McGill and co-workers found that the slip rate at Plunge Creek on the SBSAF is close to the geodetic inference (Fig. 26), while Oskin (Fig. 27) found that off-fault damage accounts for additional deformation not easily seen via fault trenching.

Additional sources of complexity in interpreting geodetic measurements in terms of fault slip are hydrologic effects, particularly due to the hydrologic barriers across faults. David Schmidt and Beth Wisely showed that motions due to changes in ground water near the SBSAF fault are large (Fig. 28). Duncan Agnew and colleagues demonstrated that an alarming deformation "event" in the San Gabriel Valley beginning in early 2005 is highly correlated with the behavior of the local aquifer.

By comparing estimated elastic strain accumulation with observed strain release in historic earthquakes, FSWG (Bird, Hager, Meade) quantified the "earthquake deficit" in southern California, hypothesizing that this deficit might lead to a higher probability of earthquakes in certain regions. Ilya Zaliapin and coworkers pointed out that these "deficits" are to be expected, given the statistics of seismicity.

Michelle Cooke and coworkers compared predictions of elastic models of deformation for alternative fault system geometries to geologic observations of uplift. They found that this comparison was useful in evaluating competing geologic models, illustrating again how interdisciplinary efforts can lead to scientific advances.

Rheological structure: The material properties of the continuum between the faults have important effects on geodetic, as well as seismic, deformation and are important in determining the dynamics of the system. Yuri Fialko and others have shown that variations in elastic modulus can have important effects on geodetic motions, both interseismic (Figure 29) and coseismic. Fault zones are now understood to have a "damage rheology" (e.g., Yehuda Ben Zion and co-workers, Jim Dieterich, Yuri Fialko and Mike Oskin). Elizabeth Hearn (Fig. 30) has investigated the implications of damage rheology for coseismic displacement, inferring that the "backslip" observed by Fialko for at the time of the Hector Mine earthquake requires regional stresses to be lower than coseismic stress changes.

Development of Community software is a high priority of FSWG. Including both realistic geometrical variations and realistic variations in rheology are critical. While important work has been done with simplified, semi-analytical models, definitive answers require the flexibility of numerical techniques such as the Finite Element Method (FEM). One of the highest priorities of the FSWG has been the development of a quasi-static, parallelized finite element code able to represent the deformation and stress fields due to all major faults in southern California, as provided by the Community Block Model, using realistic rheologies and fault behavior. Charles Williams and Brad Aagaard leveraged SCEC, NSF ITR, and Caltech resources to upgrade Tecton into a SCEC Community code, "PyLith."

An important FSWG group activity is the annual workshop: "Community Finite Element Models for Fault Systems and Tectonic Studies," organized by Mark Simons, Brad Hager, Carl Gable, Charles Williams, and Brad Aagaard. Part of the group effort is aimed at verifying code accuracy using benchmark problems. Efficient and accurate meshing of complex geologic structures is a very high priority. Gable (LANL) has taken major steps forward developing realistic models of the southern California fault system.

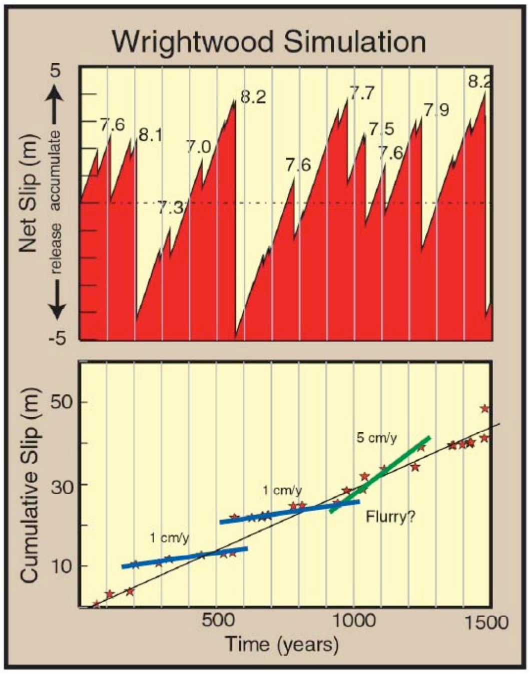


Figure 24: Earthquake simulator results for the Wrightwood paleoseismic site. (Top). Net Slip versus time for 1500 years. (Bottom) Cumulative slip versus time. Note the "flurry" of quakes between 900-1300. Results like these can be used to compare and interpret behaviors in the long record of events now known here. (S. Ward)

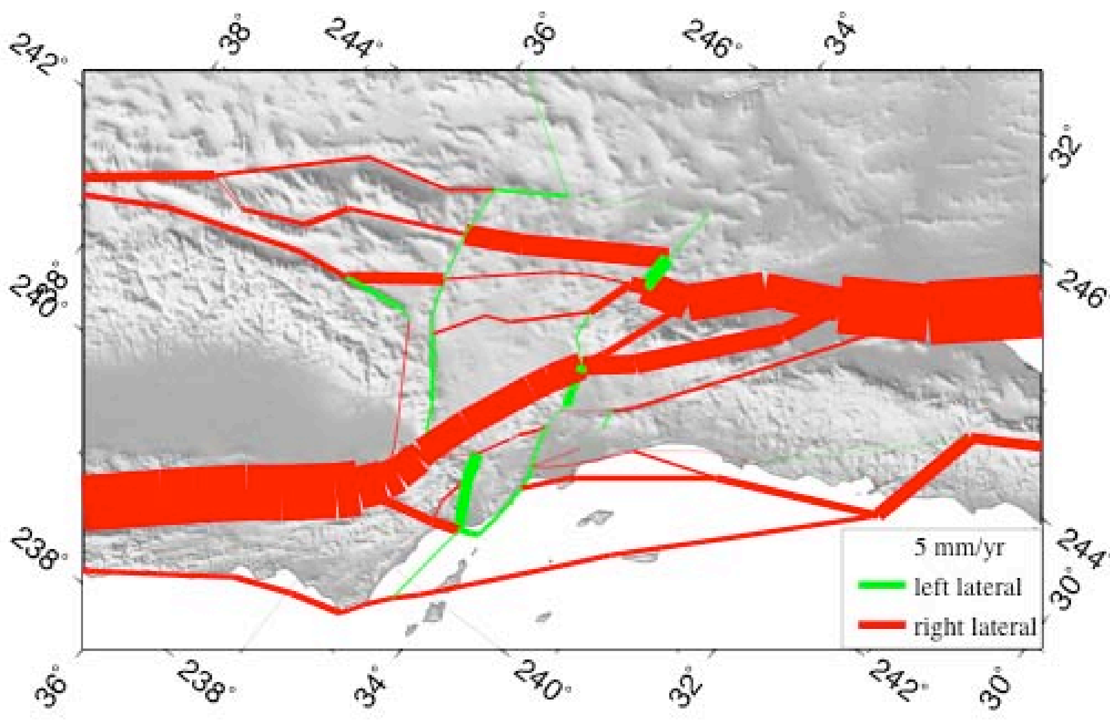


Fig. 25: Estimated strike-slip rates from the Meade & Hager block model. Red and green lines indicate right- and left-lateral motion, respectively, with width proportional to slip rate. The thickest lines represent the SAF and SJF, where ~70% of the relative plate motion is accommodated. Note the low rate on the SBSAF and the high rate across the Mojave ECSZ.

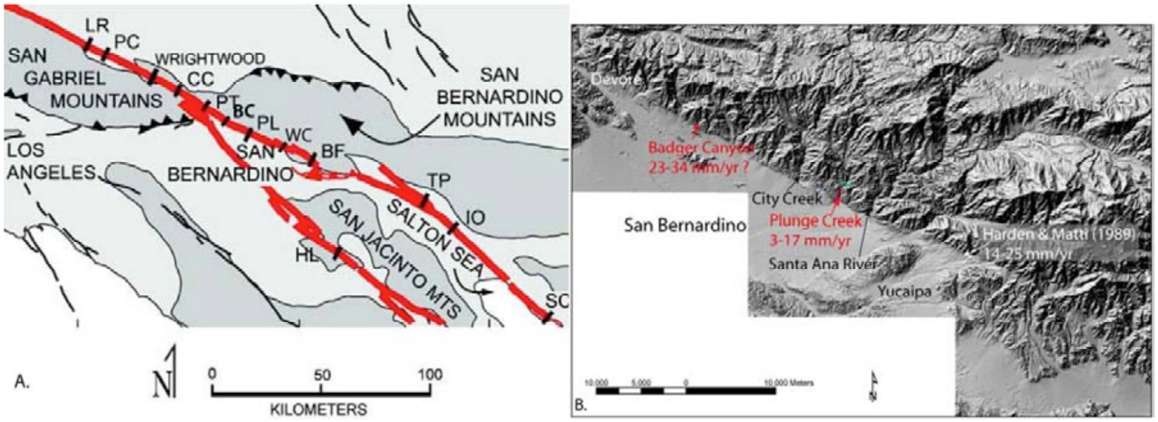


Figure 26 (S. McGill): (A) Reference map showing San Andreas and San Jacinto faults in red as well as locations of selected slip rate and paleoseismic sites. Sites mentioned in text include CC, Cajon Creek; BC, Badger Canyon; HL, Hog Lake; PL, Plunge Creek; and WC, Wilson Creek. (B) Digital elevation model showing the location of slip rate sites for the San Bernardino strand of the San Andreas fault. Weldon and Sieh's (1985) slip rate measurement of 24.5 ± 3.5 mm/yr at Cajon Creek is just beyond the northwest corner of the map.

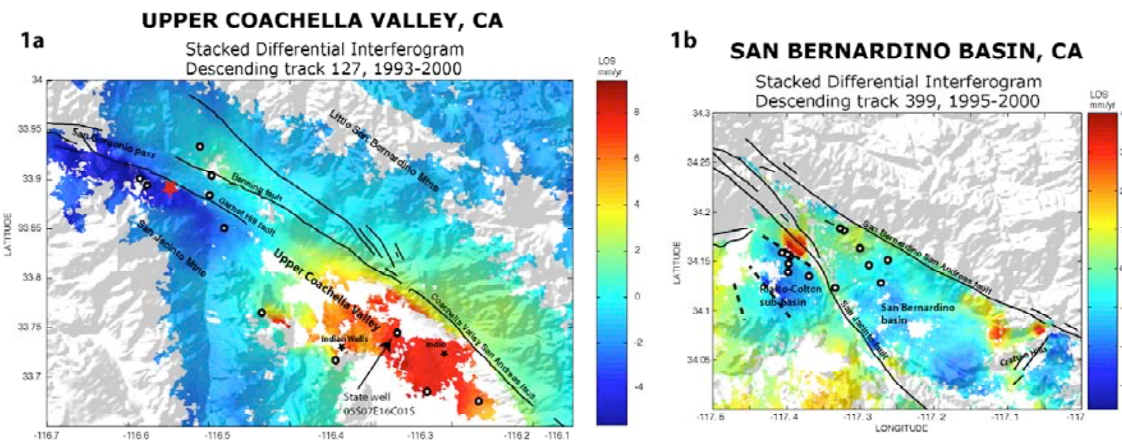


Figure 28 (Schmidt and Wisely). Stacked differential interferograms measuring satellite line-of-sight range change in mm/yr. Images are superimposed on shaded relief. Positive range change indicates motion away from the satellite, and negative range change indicates motion towards the satellite. Regions with no color are uncorrelated regions where we have no data. Individual interferograms were chosen for their good spatial coherence and minimal atmospheric contamination. Black lines are regional faults. Dotted black lines are groundwater barriers observed with InSAR timeseries. Black circles are well sites used in the initial run of HIT. The red star is the Whitewater Recharge Facility. The Coachella Valley stack, 2a, is composed of 23 individual interferograms with an average baseline of 74m. The San Bernardino stack, 2b, is composed of 30 individual interferograms with an average baseline of 65m.

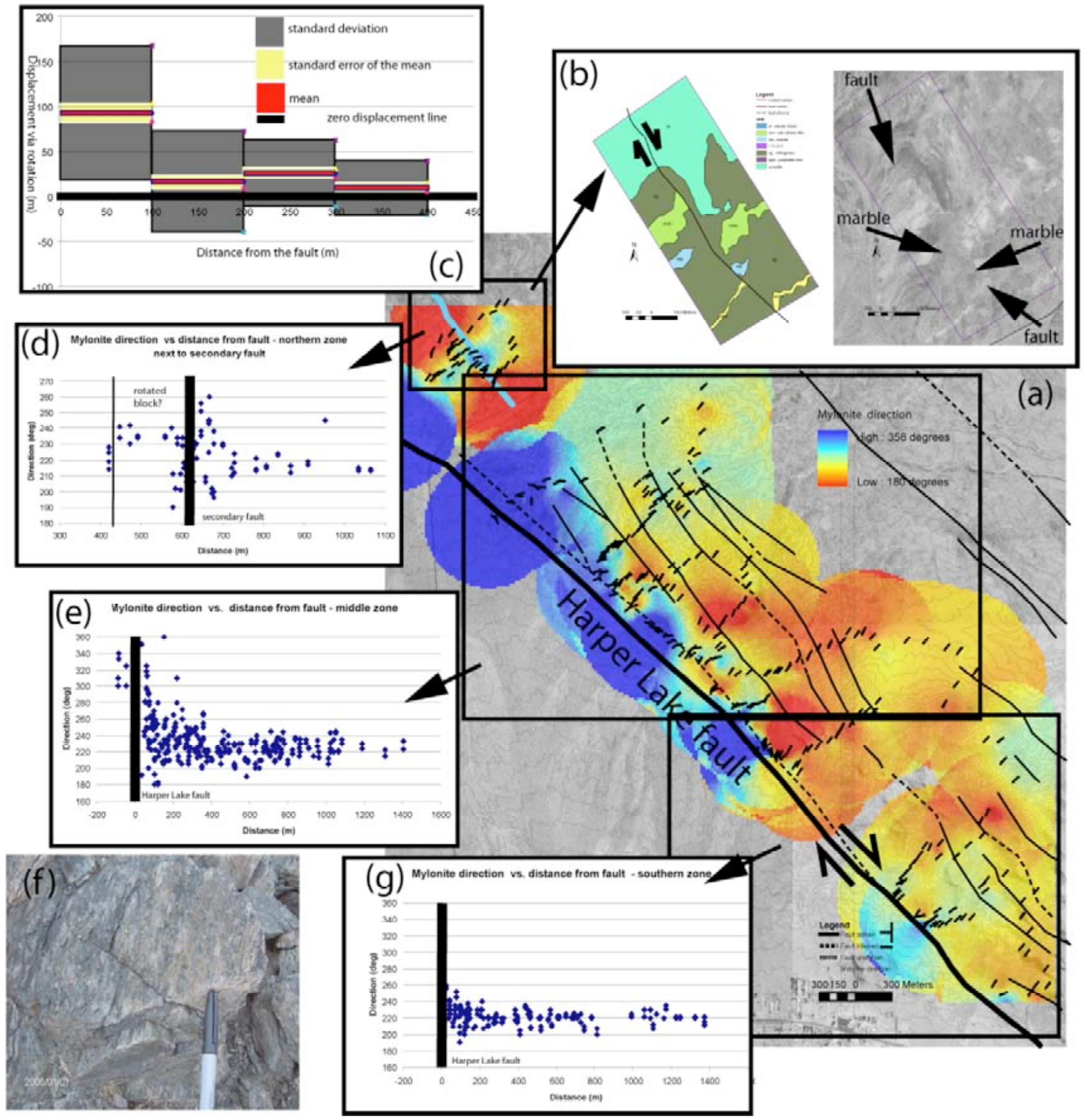


Figure 27 (From Oskin & Fialko). Example measurements of OFD, Mitchell Range, Mojave Desert, California. Early Miocene mylonitic lineations, originally oriented ~220°, are used as markers of distributed brittle shear adjacent to cross-cutting dextral Harper Lake fault. Figures described counterclockwise from right. A. Map of mylonitic lineations. Colors represent smoothed map of mylonite trends, with blue colors representing clockwise deflection of these trends next to the fault. Deformation mechanism seems to trade off along the strike of the Harper Lake fault. B. Geologic map and air photo of active secondary fault ~650 m east of and sub-parallel to the Harper Lake fault, with 200±47m offset of bedrock units. C. Graph shows values of displacement via distributed rotation in 100m bins next to the central area of the Harper Lake Fault (data graphed in e). Note that standard deviation values also increase with proximity to the fault. D. Mylonitic lineation directions graphed vs. distance in the northern map area, next to a secondary fault (in light blue on A). Vectors west of the fault are clockwise rotated by ~15° with respect to the vectors east of the fault, suggesting clockwise rotation of west block. E. Measurements of mylonitic lineations as function of distance from the Harper Lake fault in the central map area indicate a ~400 m wide zone of distributed deformation. Average distributed dextral displacement here is calculated as 143±27 m. This is ~9 ± 3% of the 3 to 4 km of total displacement across the Harper Lake fault, assuming symmetry of distributed deformation across the fault. F. Field photograph of typical outcrop of mylonite with lineation direction illustrated by pen. G. Measurements of mylonitic lineation as function of distance from the Harper Lake fault in southern map area. Insignificant variation of mylonitic lineation directions in this area indicates that distributed displacement in this zone is either small or occurs mostly by shear along secondary faults without block rotation.

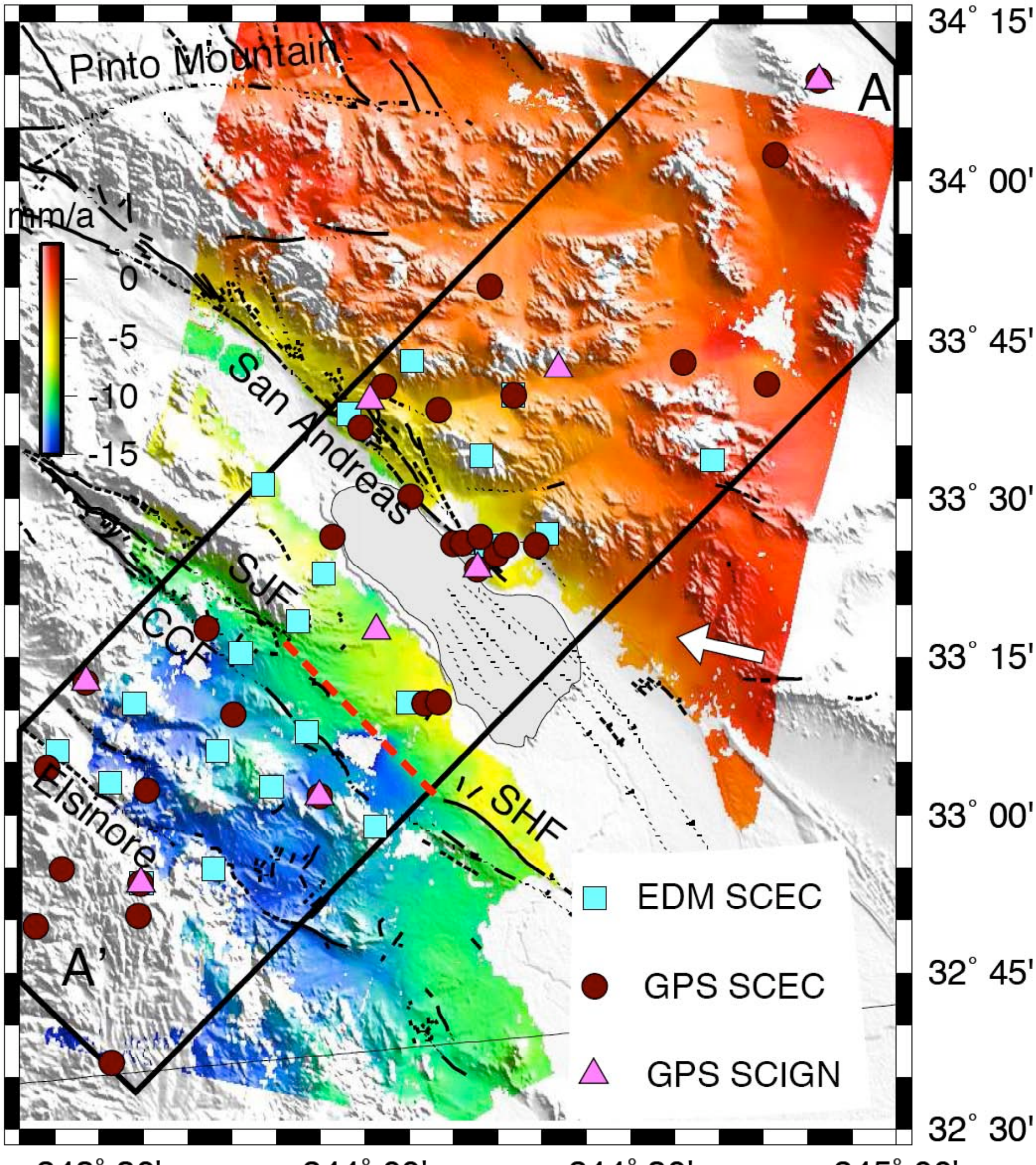


Figure 29 (Fialko): Velocity of the Earth's surface along the satellite line-of-sight (color) derived from a stack of radar interferograms spanning a time interval between 1992 and 2001. The velocity map is draped on top of the digital topography model. Black wavy lines denote the active Quaternary faults. Color symbols denote positions of the GPS (Global Positioning System) and EDM (electronic distance measurement) sites within the profile.

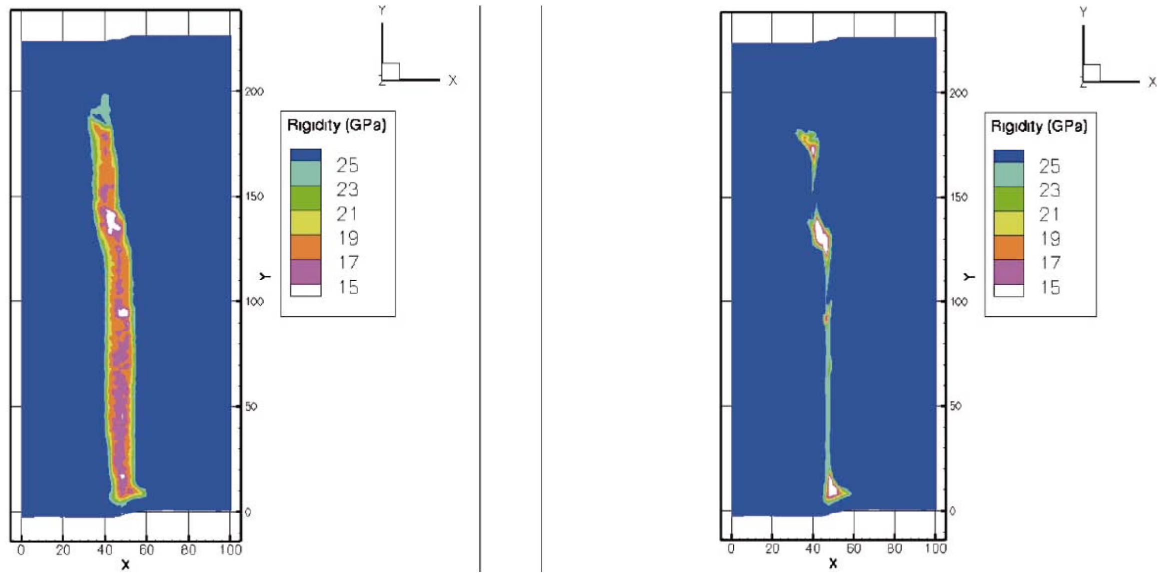


Figure 30 (Hearn). Damage-induced reduction in the rigidity modulus along a modeled fault system at 0-1 km depth (left) and 7-8 km depth (right). Tick marks on abscissa are spaced at 20 km intervals.

Structural Representation

The Structural Representation Focus Area supported SCEC 2's science mission by developing and delivering digital models of crust and upper mantle structure in southern California for use in fault systems analysis, dynamic rupture modeling, strong ground motion prediction, and earthquake hazards assessment. These efforts include development of Community Velocity Models (CVM & CVM-H), Community Fault Models (CFM & CFM-R), and a Community Block Model (CBM). Together, these models comprise a Unified Structural Representation (USR).

The Structural Representation Focus Area was a new element of SCEC 2, created to ensure that various efforts in earthquake system science where able to use comprehensive, state-of-the-art structural models vetted by the scientific community. The Focus Area developed two alternative Community Velocity Models (CVM, Magistrale et al., 2001; and CVM-H, Suess and Shaw, 2003). Both models are 3D descriptions of crust and upper mantle compressional velocity (v_P) with derivative shear-wave velocity and density models. CVM v. 4.0 (Figure 31) employs a rule-based approach for defining the velocity structure in sedimentary basins (Magistrale et al., 2000), which are embedded in regional tomographic (Hauksson, 2000) and 1D background models. The Focus Area also developed a new, alternative velocity parameterization termed the CVM-H, based on tens of thousands of direct velocity measurements from petroleum well and seismic reflection data (e.g., Suess & Shaw, 2003). Provision of this new model reflects the commitment of SCEC to deliver alternative structural representations that reflect epistemic uncertainties. Moreover, this new model includes a basement surface compatible with the positions and offsets of major faults represented in the SCEC Community Fault Model (CFM 3.0). Thus, together the CFM 3.0 and CVM-H 4.0 represent a unified structural representation, or USR.

The Community Velocity Models are being used in a variety of SCEC sponsored research projects including numerical simulations of seismic wave propagation, earthquake catalog relocations, and other efforts to characterize earthquake sources. The models have also been used for earthquake source inversions, both as point sources (Liu et al., 2004) and finite sources (Chen et al., 2005b), and as the basis for development of fully 3D, waveform tomographic inversion models of crust and upper mantle structure (Chen et al., 2004, 2007; Liu et al., 2006). These waveform inversion studies are able to assess the accuracy of the SCEC CVM's based on comparisons of observed and synthetic waveforms, and offer the promise of significantly improving the structural representations particularly in regions of poor data control. Moreover, the CVM's are being used in a series of scenario simulations (e.g., TeraShake; Minster [2004], CyberShake; Callaghan et al., [2006]) to quantify expected strong ground motion that will result from future large earthquakes in southern California. These simulations offer the potential of significantly improving regional seismic hazards assessment, and through the SCEC Implementation Interface will be used in collaboration with the earthquake engineering community to assess the impacts of expected ground motions on building and structures.

The CFM is an object-oriented, 3-D representation of active faults in southern California that are deemed capable of generating moderate to large earthquakes (Plesch et al., 2004; 2007).

Faults are defined by surface geology, earthquake hypocenters and focal mechanisms, well bore, and seismic reflection data. The latest version of the CFM (version 3.0) (Figure 32) represents a comprehensive model of more than 150 preferred fault representations, which were defined based on an extensive review process involving more than 20 SCEC investigators and participants from the California and U.S. Geological Surveys. This evaluation was conducted through a series of workshops, in which scientists used the LA3D software tool, developed by the SCEC Intern Program, to visualize and analyze the faults. In addition to the preferred model, the new release offers sets of viable, alternative representations in different geographic regions. Moreover, we produced versions of the model with faults represented in different ways in order to support their use with numerical methods and applications that cannot directly employ triangulated surfaces, which is the manner in which faults are represented in the CFM. The Community Block Model, or CBM, is a version of the model where about 50 of the most important faults were used, along with topography and Moho surfaces, to developed closed, fault-bounded blocks in southern California. The CBM, in turn, is being used to develop computational meshes for use in finite element models of fault system behavior. Moreover, we developed a version of the CFM where faults are represented as rectilinear segments. The rectilinear Community Fault Model (CFM-R 3.0), mirrors the fault inventory in CFM 3.0, and is currently being used as a basis for SCEC and the Working Group on California Earthquake Probabilities (WGCEP) re-assess regional earthquake hazards. Collectively, this series of fault models, including the CFM, CFM-R, and CBM, is intended to support a wide variety of SCEC science in strong ground motion prediction, fault systems modeling, and seismic hazards assessment.

The process of designing, developing, and testing these community models has served an important role in coordinating geologic and seismologic investigations of fault systems and basin structure in southern California. Specifically, efforts supported by the Structural Representation Focus Group have substantially revised our understanding of the nature, and in many cases the inventory, of active fault systems throughout California, most significantly in the Ventura basin and Santa Barbara Channel (e.g., Kammerling et al., 2003), the northern Los Angeles basin (e.g., Shaw et al., 2002; Dolan et al., 2003; Carena, 2003; Griffith and Cooke, 2004), the California Borderlands (e.g., Legg et al. 2002; Rivero, 2000; Sorlien et al., 2004), and the Eastern California Shear Zone. Delivery of the models through the SCEC IT framework ensures that results of these investigations are distributed within and beyond SCEC for use in a wide range of earthquake science, hazard characterization, and education and outreach activities. A key aspect of these community models is that they provide alternative representations – both of contentious faults in the CFM and basin velocity structure in the CVM. Competing views of faults and basin structures represented in these models have inspired collaborations between mechanical modelers, geologists, and geodesists to evaluate alternative structural representations, and develop new and improved versions of the community models.

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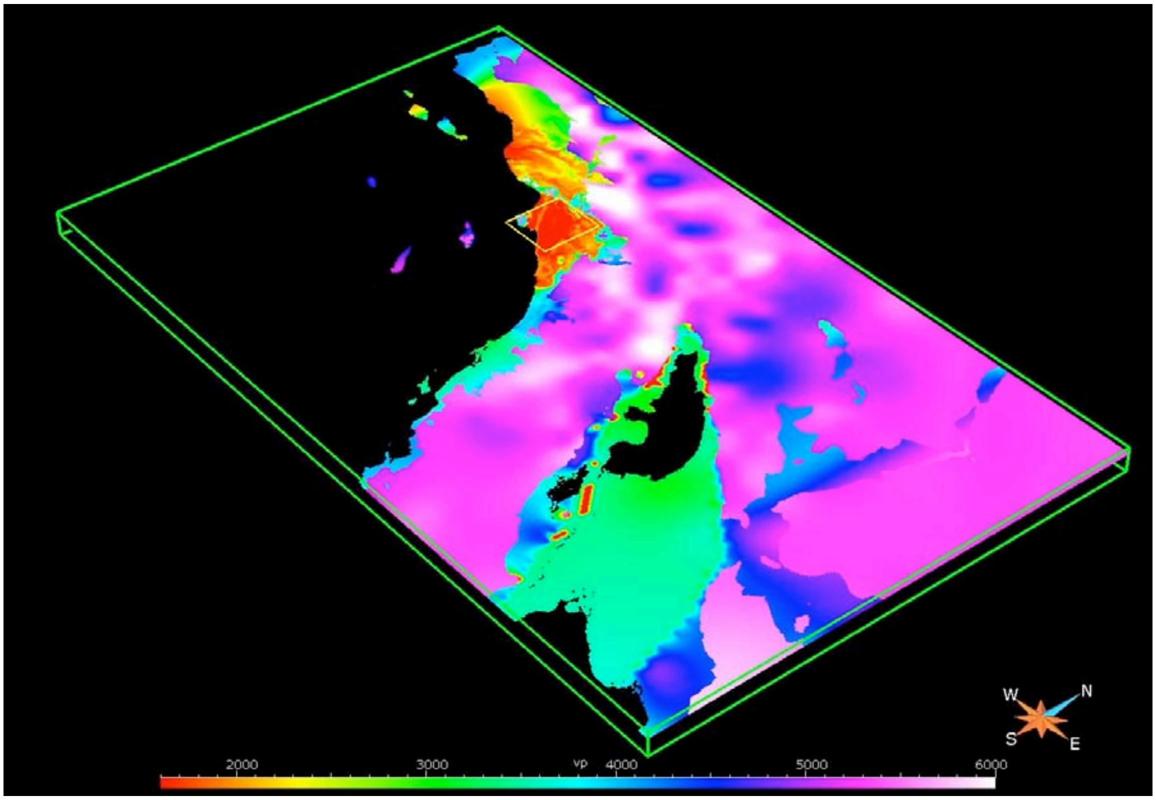

Figure 31: Perspective view of the SCEC Community Velocity Model (CVM-H 4.0) (Suess and Shaw, 2003). Low velocity regions represent sedimentary basins that are embedded in regional tomographic model of Hauksson (2000).

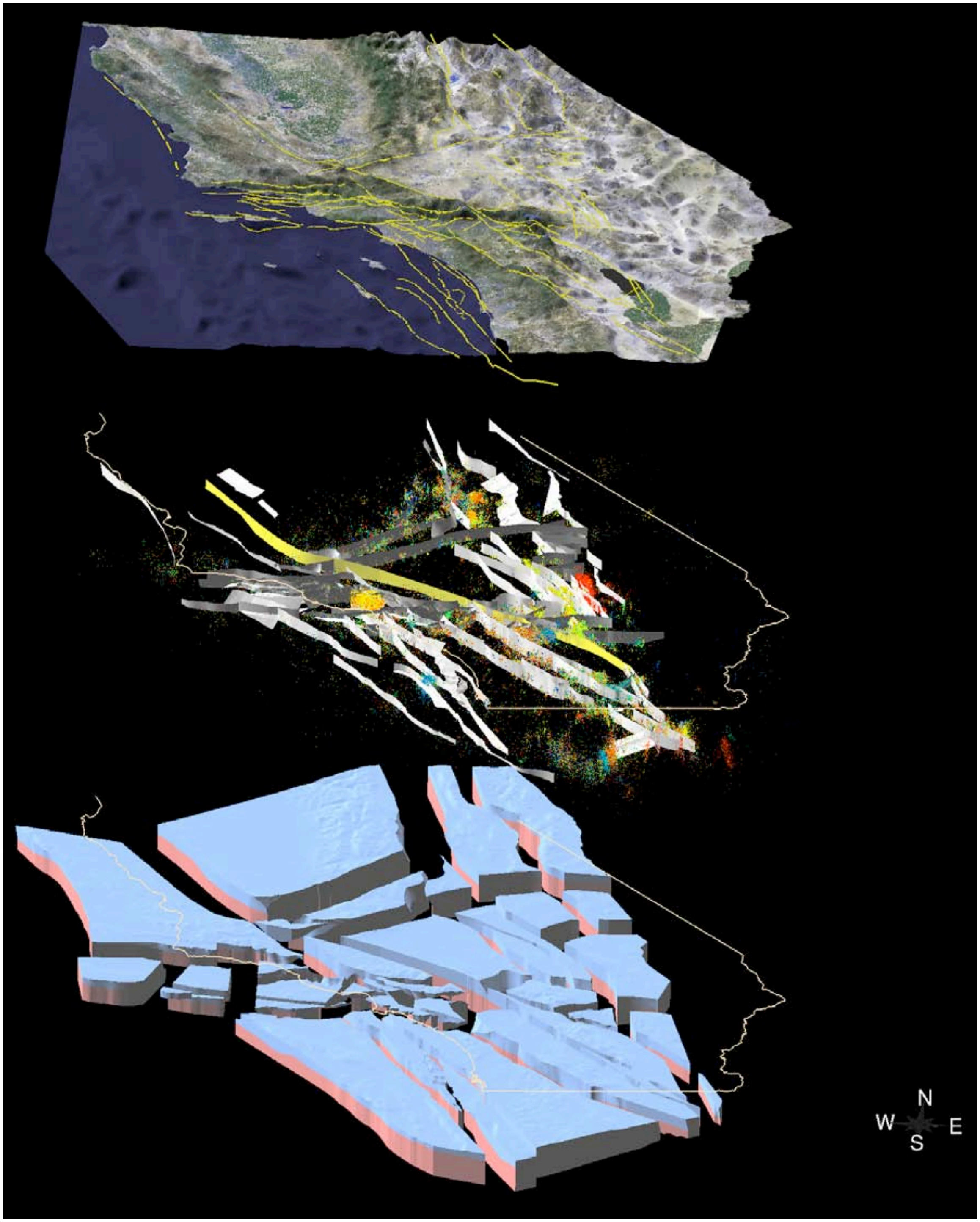

Figure 32: Perspective views of the elements that comprise the SCEC Community Fault (CFM) and Block (CBM) models. (top) Multispectral satellite image draped on digital elevation model, with map traces of faults in the CFM. (middle) The Community Fault Model (CFM) with seismicity (M > 1, 1984 - 2003). The model is composed of triangulated surface representations of more than 140 active faults, including the San Andreas Fault (SAF) (shown in gold), the Eastern California shear zone (ECSZ), and blind-thrust faults in the Los Angeles basin. Seismicity (Hauksson, 2000) is color coded by date.

Ground Motion

The primary goal of the Ground Motion Focus Group is to predict ground motions using physics-based methods that account for source complexity and 3D geologic structure. During SCEC2 significant progress has been made toward this goal, particularly in the following areas: (1) Simulate low-frequency ground motions (< 0.5 Hz) using the CVM, realistic source models, and validated numerical codes; (2) Formulate stochastic methods for predicting high-frequency ground motions, and combine them with the low-frequency deterministic methods to attain a broadband (0-10 Hz) simulation capability; (3) Collect observations to test broadband ground motion predictions, including precarious-rock data and other geologic indicators of maximum shaking intensity and orientation; and (4) Apply SCEC's ground-motion simulation capabilities to improving SHA intensity-measure relationships and creating realistic scenarios for potentially damaging earthquakes in Southern California.

Low Frequency Simulations for Scenario Earthquakes

In a collaborative study sponsored by SCEC and the PEER-Lifelines program, five groups of researchers participated in extensive testing of procedures for simulating ground motions in basins using 3D finite difference and 3D finite element methods. This process resulted in the virtual elimination of discrepancies among the five simulation procedures. These groups then participated in the simulation of six different earthquake rupture scenarios on each of ten faults in the Los Angeles region (Day et al, 2007). The results of these simulations were used to develop relationships between ground motion amplification and the depth of the basin, expressed as the depth to 1.5 km/sec, for response spectral amplitudes in the period range of 2 to 10 seconds. The resulting mean basin-depth effect is period dependent, and both smoother (as a function of period and depth) and higher in amplitude than predictions from local 1D models (Figure 33). These amplification factors have been used in the development of ground motion prediction models of the NGA-E project.

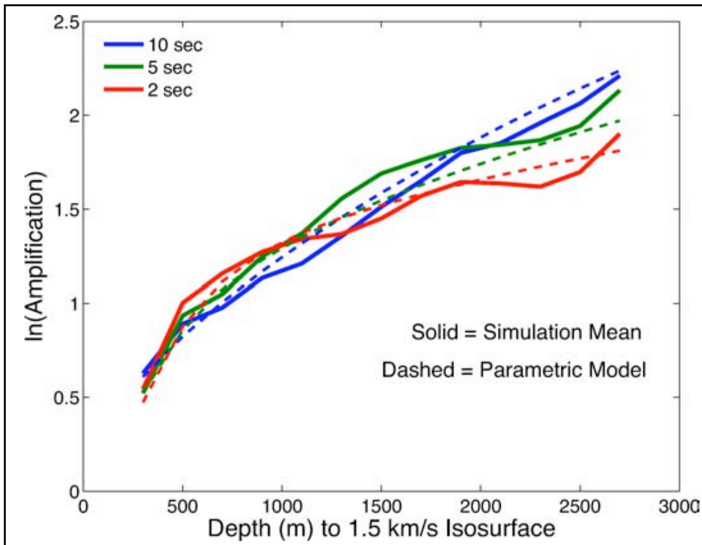

Figure 33: Natural logarithm of the basin amplification factor, as a function of depth to the 1.5 km/s *S* velocity isosurface.

Broadband Ground Motion Simulations

The Puente Hills blind thrust has been the subject of particular scrutiny. This significant hazard to Los Angeles has been characterized only recently, and it not portrayed in the 1997 Uniform Building Code. Figure 34 shows a full broadband (0-10 Hz) simulation of an earthquake caused by a Northridge-type rupture occurring on the Los Angeles segment of the Puente Hills system (Graves and Somerville, 2006). This simulation is unprecedented in scope and scale, producing three component, broadband ground motion time histories at over 66,000 locations covering most of the greater Los Angeles metropolitan region. Analyses of building response to these simulated ground motions are currently being performed in a pilot project on end-to-end simulation, sponsored in part by the SCEC Implementation Interface grant, which was jointly funded in 2004 by the CMS and EAR divisions of NSF.

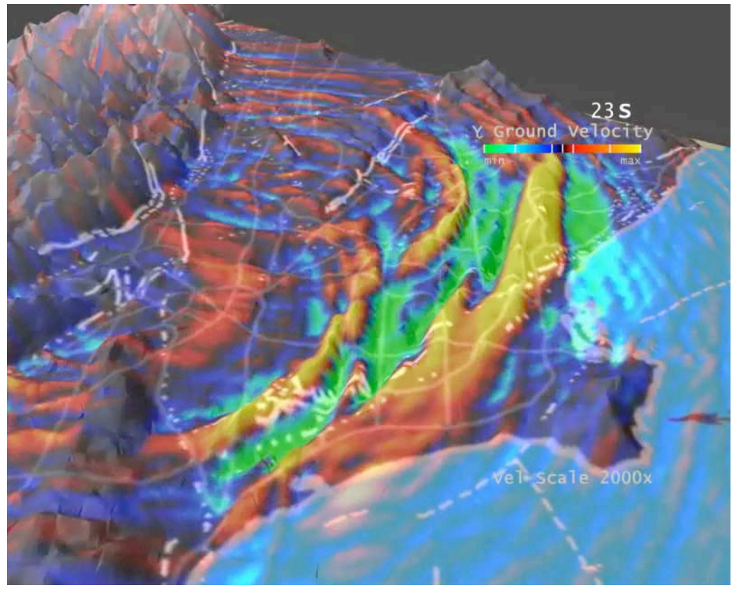

Figure 34: Broadband (0-10 Hz) ground motion simulation for the Puente Hills fault. Strong rupture directivity channels large amplitude pulses of motion directly into the Los Angeles basin, which then propagate southward as basin surface waves.

Following the successful models of the 3D Basin Modeling Project Group and the Rupture Dynamics Simulation Group, we have begun the formation of a Broadband Ground Motion Simulation Group. The first activity of this group was a workshop held in late January 2005. Among the main activities of this workshop was a validation exercise using ground motion data from the 1994 Northridge earthquake. Six modeler groups submitted simulation results for the exercise and the results were compared to the observations using several goodness-of-fit measures. Most of the simulation methods work well at the longer periods (T > 2 sec). At the shorter periods, some methods (primarily those with stochastic components) work well, while others tend to under-predict the observed levels of ground motion. It is clear that rupture model characterization, particularly at the shorter periods (T < 1 sec) plays a critical role in the simulation of ground motions.

Precarious Rocks

One of the hallmarks of SCEC is its support of innovative approaches to scientific research. A prime example of this is the ongoing investigation of precariously balanced rocks. These studies have documented precarious rock sites along several major faults in southern California, including the San Andreas, Whitewolf, Elsinore, and San Jacinto. The Ground Motion group has been analyzing these data to help provide constraints on estimates of peak near-fault ground motions that have occurred during paleo-earthquakes. These studies have recently identified a number of such rocks along a 70-km line almost midway between the Elsinore and San Jacinto faults. Paleoseismic studies indicate that these rocks have experienced about six M 7 earthquakes every thousand years. Recent work by Purvance et al (2004) has shown that rock toppling requires both an acceleration above some threshold (to start a rocking motion), and subsequent longer period motion (e.g., large peak velocity) near its rocking period. Such a joint occurrence of multiple ground motion intensity measures falls within the framework of vector-valued probabilistic seismic hazard analysis (VPSHA). Thus, study of the precarious rocks has direct relevance to understanding the response of engineered structures such as tall buildings, which may have a significant contribution not only at its fundamental mode, but also its first higher mode. Purvance et al (2004) applied VPSHA to show that the presence of precariously balanced rocks between the San Jacinto and Elsinore faults appears to be inconsistent with current empirical ground motion models.

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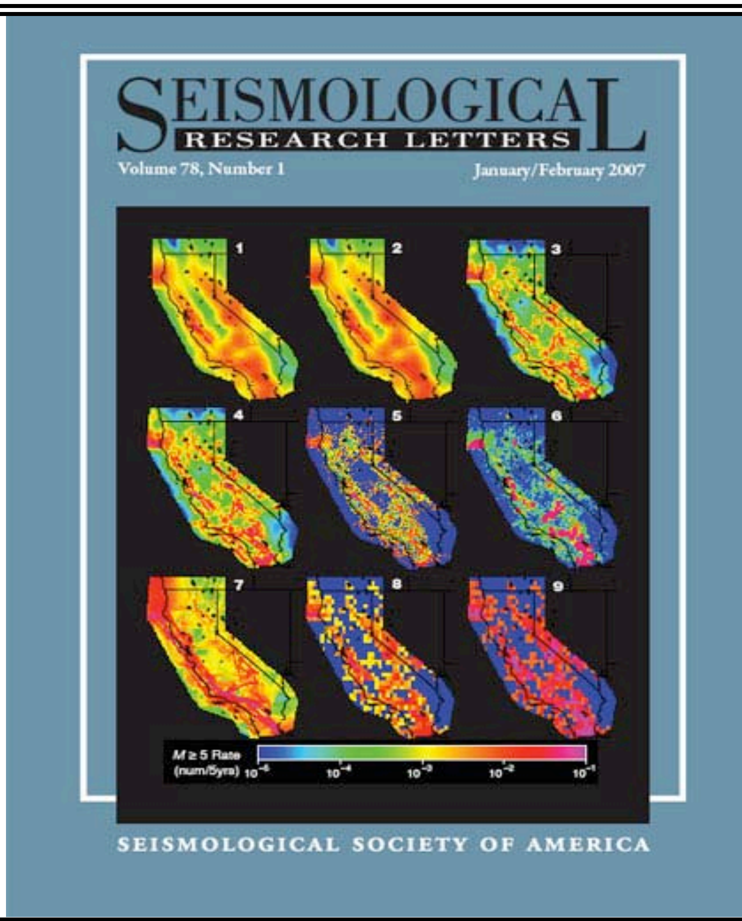
SCEC 2 SHA Focus Group
Final Report

There has been consensus that significant improvements in seismic-hazard analysis (SHA) will require a more physics-based approach to modeling. This applies to forecasting both where and when faults will rupture (an Earthquake Rupture Forecast, or ERF), as well as predicting the consequent ground shaking, or more specifically, the probability that some intensity measure of engineering interest will be exceeded given fault-rupture event. Unfortunately there is no consensus on how to construct more physics-based models, which means we need to both encourage the development of viable alternatives, as well as be able to accommodate different models in SHA. In fact, proper SHA requires that different viable models be included in the analysis (to adequately represent "epistemic" uncertainties). Given this need for alternative models and an SHA computational infrastructure capable of handling them, the two primary projects of the SHA Focus Group in SCEC 2 were RELM & OpenSHA.

RELM:

RELM was the working Group for the development of Regional Earthquake Likelihood Models (http://www.RELM.org). Given the lack of consensus on how to forecast earthquakes, the goal of RELM was to: 1) develop a variety of viable forecast models for California; 2) formally test these models against observations; and 3) evaluate the seismic hazard implications of each. These goals were satisfied in SCEC 2, and are documented in a special issue of *Seismological Research Letters*:



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In SCEC 3 RELM has evolved into the following projects:

- CSEP - A collaboratory for formal testing of earthquake forecasts and predictions (http://scecdata.usc.edu/csep)

- WGCEP - A group for combining "best available science" into official forecasts for California (http://www.WGCEP.org)

- SCEC's "Earthquake Forecasting and Predictability" focus group (for basic research)

OpenSHA:

As discussed above, we previously needed a computational infrastructure for SHA that can accommodate a rapid proliferation of new, alternative, and more physics-based models. Our answer to this in SCEC 2 was the development of *OpenSHA* (http://www.OpenSHA.org), which is open source, object-oriented (modular), multiplatform, web accessible, and graphical-user-interface (GUI) enabled. The framework allows any arbitrarily complex (e.g., physics based) earthquake-rupture forecast, ground-motion, or engineering-response model to “plug in” for analysis without having to change what’s being plugged into. Furthermore, any of the data or modeling components can be deployed and accessed from anywhere over the internet using distributed object technologies (Field et al., 2005a; Maechling et al., 2005a; see example in Box 2). We are also using GRID computing at access idle computers in order to expedite large computational problems (Field et al., 2005b; Maechling et al., 2005b; see example in Box 3). This software platform is being used to solve cutting-edge problems that have a first-order impact on society, such as the probable losses given large earthquakes under Los Angeles (see example in Box 4). More information can be found at our web site, including: *Mission Statement, Overview, Applications, Accomplishments, Near-Term Goals, Documentation, Publications, Getting Involved, Source Code, Development Team, and Contact Info*:

http://www.OpenSHA.org

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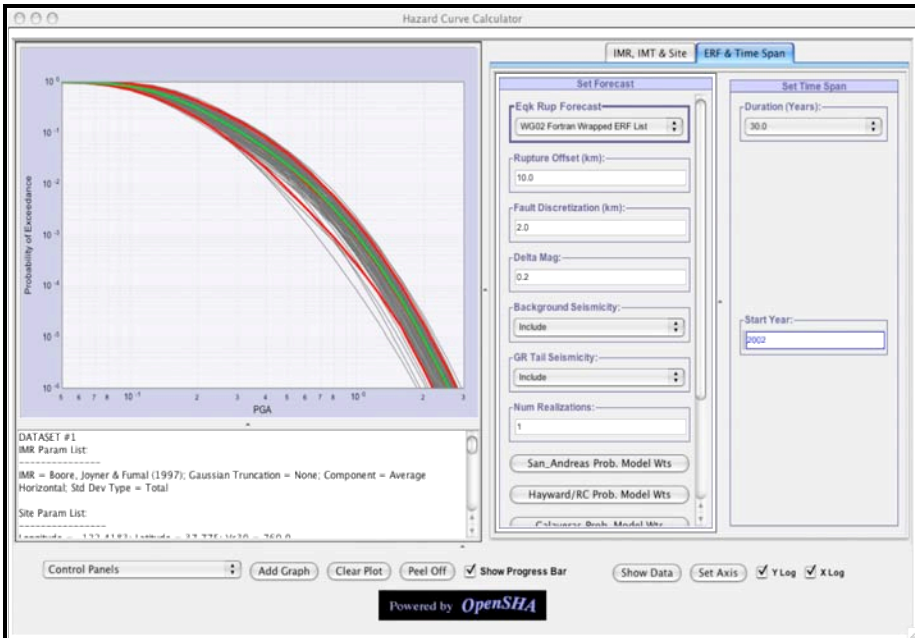
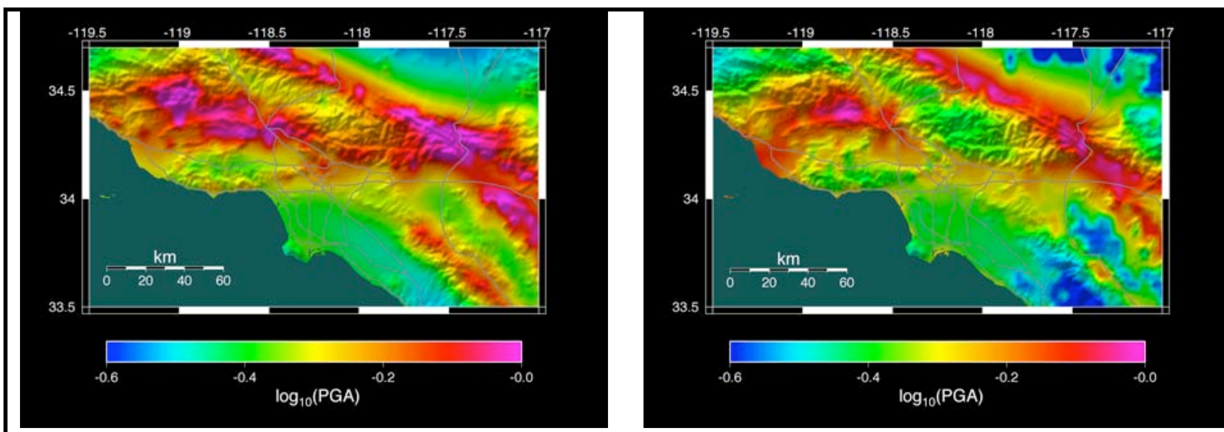
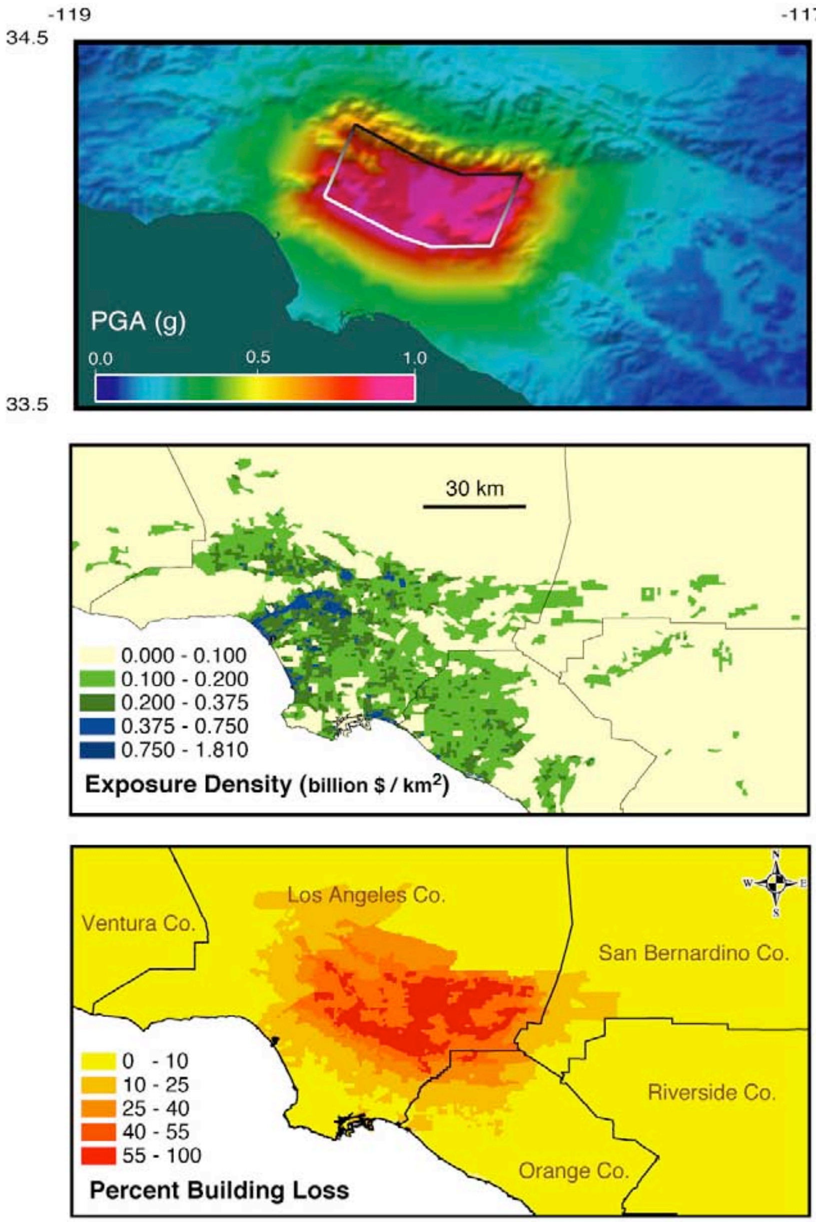


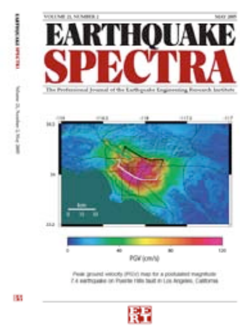
Box 2. This is a screenshot from the OpenSHA hazard curve calculator, showing 30-year PGA hazard curves for downtown San Francisco based on the ERF from the 2002 Working Group on California Earthquake Probabilities. This ERF is the most sophisticated forecast model ever developed, both in terms of it being time dependent and in accounting for numerous epistemic uncertainties. The gray lines represent the range of values given these uncertainties, the red curves represent 90% confidence bounds, and the green curve is the mean or "best" estimate. This ERF is deployed as Java-wrapped Fortran code that resides on a server and can be accessed by the application from anywhere over the Internet. The Boore et al. (1997) IMR (attenuation relationship) was used for this calculation, although any of the other supported models could have been chosen as well. This image if from Field et al. (2005b).



Box 3. Full probabilistic PGA hazard maps, including site effects, computed for the LA region using the ERF applied in our national hazard maps (Frankel et al., 2002). The map on the left was produced using the Abrahamson and Silva (1997) IMR (attenuation relationship), and that on the right was made with the Boore et al. (1997) relationship. Note that one implies the hazard in the San Gabriel mountains is relatively high compared to the adjacent LA basin, whereas the other implies the opposite; this is a manifestation of assumptions related to nonlinear sediment amplification. The application that generates these data utilizes GRID computing, where the computational load is distributed over any idle UNIX computers in USC's Condor pool (Maechling et al., 2005b, *SRL* **76**, 581-587). This reduces computation time by more than an order of magnitude. These images come from Field et al. (2005c).



Box 4. (top) peak-ground-acceleration (PGA) shaking map for a magnitude 7.5 Puente Hills earthquake beneath Los Angeles (computed using the an OpenSHA application available to anyone). Also shown is the regional building exposure (middle) and earthquake losses (bottom) computed for this event using FEMA's HAZUS loss estimation software. With these tools one can now perform such loss estimates for virtually any earthquake using a variety of ground-motion models and site effect treatments. These plots are from a comprehensive, probabilistic loss analysis that has been published in:



(Field et al., 2005a)

Information Technology/SCEC Community Modeling Environment (CME)

Introduction

During SCEC 2, SCEC researchers have organized and lead two large research projects that emphasize the application of numerical modeling and high performance computing to seismic hazard research. These two projects, the SCEC Community Modeling Environment (SCEC/CME) Project (EAR-0122464), and the SCEC Petascale Cyberfacility for Physics-based Seismic Hazard Analysis research Project (PetaSHA) (EAR-0623704), were funded through NSF grants that are separate from the core SCEC grant. While they are funded separately from the core SCEC program, both of these projects were designed to advance aspects of the core SCEC research program. The SCEC/CME project was active from October 2001 through September 2006. The PetaSHA project is currently active, starting in October 2006 and continuing through September 2008. While the project names have changed, we continue to refer to the group working on these projects as the CME collaboration.

The CME collaboration performs basic research in both the geosciences and in computer science. The geoscience research is focused on the problem of seismic hazard analysis. The computer science research includes research in grid computing, large scale data management, high performance computing, and scientific workflows. The research activities have remained focused on developing new, physics-based techniques for seismic hazard research. Our research results on these projects include Probabilistic seismic hazard analysis (PSHA), earthquake wave propagation, dynamic rupture simulation, as well as 3D tomography using inversion.

In the first two years of the SCEC/CME project, the project activities focused on software and tool development including development of PSHA codes such as OpenSHA. During SCEC/CME project years 3 and 4, large scale simulation projects were performed. During SCEC/CME Year 5, the SCEC/CME project worked on at least three different large-scale high performance computing efforts, TeraShake 2, CyberShake, and the SCEC Earthworks Science Gateway.

The PetaSHA research activities are increasingly oriented towards applying high performance computing to SCEC research. Currently, on the PetaSHA project, the CME collaboration runs simulations that make use of the tools and infrastructure developed earlier on the SCEC/CME project as well as developing new simulation capabilities. On the PetaSHA project, we are working to increase the scale and resolution of the PSHA simulations in order to include more realistic physics in our simulations. As we increase the scale and resolution of these simulations, we require larger and faster computers. Currently, the CME collaboration is scaling up our codes to work on the largest computer systems possible. These projects were performed in collaboration between SCEC/CME researchers and USC High Performance Computing groups and the NSF TeraGrid organization. Each of these simulation efforts each helped to advance SCEC research goals.

In addition to a program of simulation-based science, the CME collaboration performs basic research in computer science areas including scientific workflows and application of knowledge representation to workflow planning. The group also performs extensive Education and Outreach efforts with presentations of SCEC research at numerous geophysical and computer science conferences. The SCEC/CME, and now the PetaSHA project, provides support for the SCEC Undergraduate Experiences in Information Technology (UseIT). The UseIT program has provided research experiences in both the geosciences and computer science for numerous undergraduate students over the last six years.

Description of Computational Pathways

The simulations needed for physics-based SHA can be organized into a set of computational pathways. For example, conventional PSHA computes an *IM* from an *AR* using sources from an *ERF*, which we schematically represent as *Pathway 1*: $ERF \rightarrow AR \rightarrow IM$.

In physics-based PSHA, intensity measures are calculated directly from the ground motion: $GM \rightarrow IM$. The ground motion is predicted from 4D simulations of *dynamic fault rupture* (*DFR*) and *anelastic wave propagation* (*AWP*). In some cases, especially for sites in soft soils, a *nonlinear site response* (*NSR*) may be included in the ground-motion calculations. The complete computational pathway can thus be written as $DFR \leftrightarrow AWP \rightarrow NSR \rightarrow GM$.

The double-arrow indicates that rupture propagation on a fault surface is dynamically coupled to the seismic radiation in the crustal volume containing the fault. However, the *DFR* can be represented by an equivalent *kinematic fault rupture* (*KFR*). Therefore, the earthquake calculation can be split into the simulation of ground motions from a kinematic source: $KFR \rightarrow AWP \rightarrow NSR \rightarrow GM$ (*Pathway 2*), and the dynamic rupture simulation: $DFR \leftrightarrow AWP \rightarrow KFR$ (*Pathway 3*).

The source descriptions S_n for the *ERF*s used in conventional PSHA do not contain sufficient information for physics-based PSHA. In addition to the rupture area A_j and magnitude m_j, the *KFR* for Pathway 2 simulations must specify the hypocenter, the rupture rise-time and velocity distributions, and the final slip distribution. Stochastic "pseudo-dynamic" *KFR* models that reproduce the variability observed in these parameters for real earthquakes are a major topic of seismological research. Pathway 3 simulations are an important tool for investigating the stochastic aspects of dynamic ruptures, and they can be used to constrain an "extended" earthquake rupture forecast, *ERF**, which specifies a complete set of the *KFR* probabilities. The physics-based PSHA calculation can then be written as: $ERF^* \rightarrow AR^* \rightarrow IM$ (*Pathway 1**), where *AR** is the attenuation relationship obtained from the Pathway 2 simulations.

Instantiation of the 4D simulation elements requires information about the 3D geologic environment. For example, *DFR* depends on the fault geometry, the mechanical properties on both sides of the fault surface, and the stress acting on the fault, whereas *AWP* depends on the density, seismic velocities, and attenuation factors throughout the lithospheric volume containing the source and site. The databases needed to represent the 3D geologic environment for the complete *GM* simulation defines a *unified structural representation* (*USR*). SCEC's USR Working Group has developed a suite of 3D community models that provide a *USR* for Southern California. Nevertheless, many of the current limitations on ground-motion simulations are related to the lack of details in the *USR*, such as inadequate spatial resolution of seismic wavespeeds. Improvement of the *USR* by the *inversion* (*INV*) of observed ground motions constitutes a difficult but important computational pathway: $GM_{obs} \rightarrow INV \rightarrow USR$ (*Pathway 4*).

Computational solutions to the inverse problem require the ability to solve, often many times, the forward problems of Pathways 2 and 3. In particular, *INV* for full 3D seismic waveform tomography can be constructed as *AWP†*, the adjoint of anelastic wave propagation, analogous to inversion and data-assimilation methods in oceanography and other fields. The SHA computational pathways are summarized in the figure 35 below.

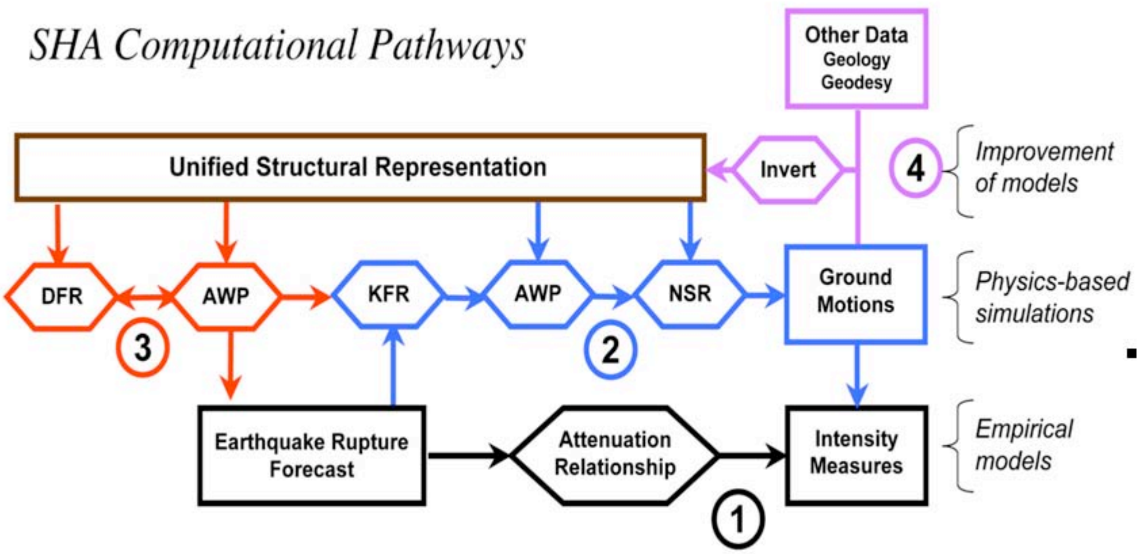


Figure 35: SCEC PSHA Computational Pathways

Development of SCEC Computational Platforms

The computing model that has been developed by the CME collaboration is organized around the concept of *computational platforms*. We define a computational platform as a vertically integrated collection of hardware, software, and people that provides a broadly useful research capability.

The concept of computational platforms emerged out of our experiences on the CME project. On the CME project, many of our large scale simulations required us to integrate SCEC geophysical application codes with existing cyberinfrastructure. Once our codes were integrated with the existing cyberinfrastructure, computer scientists and geoscientists were needed to run the programs and to interpret the results. We describe the process of integrating across these different areas as vertical integration.

SCEC computational platforms have several common characteristics. A computational platform includes validated simulation software and geophysical models. A computational platform provides re-usable simulation capabilities. A computational platform can import parameters and from other systems and export results to other systems. A computational platform typically requires access to high performance computing capabilities and data and metadata management tools. A computational platform may use scientific workflow capabilities to run a sequence of programs one after another in an automated manner.

SCEC has now developed several computational platforms and is currently proposing to develop several more. Figure 36 shows the current group of existing, and proposed platforms. Many of the platforms have similar names, so we will provide a brief description of each in the following sections.

OpenSHA Platform

OpenSHA is an object-oriented, web-enabled, open-source platform developed under the ITR program in partnership with the USGS (N. Field, lead) for a variety of Pathway 1 calculations, including the comparisons of hazard curves and maps from different PSHA models. Through its plug-and-play architecture, it can accommodate essentially all types of *ERF*s, *AR*s, and *IM*s. The OpenSHA platform has been extensively validated and is now fully operational, and its use of grid-based workflows puts capability-computing power at the disposal of PSHA researchers.

TeraShake Platform

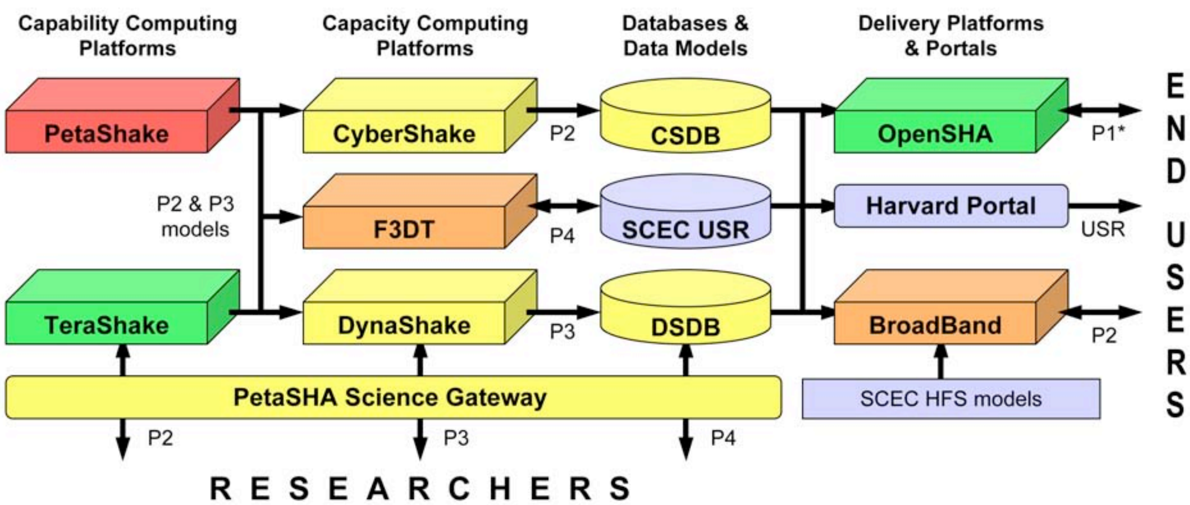


Fig. 7. The PetaSHA-2 cyberfacility, showing the proposed array of computational platforms. *TeraShake* and *OpenSHA* are operational platforms (green boxes) developed under ITR funding. *CyberShake* and *DynaShake* and their respective databases, *CSDB* and *DSDB*, are in advanced stages of development (yellow) under current EAR funding. The proposed *F3DT* and *BroadBand* platforms are in the demonstration stage (orange). *PetaShake* is the petascale platform (red) proposed to OCI/PetaApps. *P1** and *P2-P4* are the computational pathways described in §A.1. Researchers will access codes and results from the PetaSHA science gateway, and users will access validated models and data products through two delivery platforms, *OpenSHA* and *BroadBand*. PetaSHA-2 will also provide meshing services for the SCEC Unified Structural Representation (*USR*), which will be delivered to users through the SCEC/Harvard gateway, and it will host the SCEC High-Frequency Stochastic (*HFS*) models. These components (blue) will be supported by SCEC base grants from EAR and USGS.

Figure 36 above

TeraShake is the CME's first capability-computing platform, designed to perform both Pathway 2 and Pathway 3 calculations using the SCEC 3D Community Velocity Models (CVMs). Early validation exercises for anelastic wave propagation (*AWP*) simulations verified the accuracy and scalability of candidate codes. The Olsen *AWP* fourth-order finite difference (FD) code was optimized to run on hundreds of processors. The TeraShake platform also includes the CMU Hercules finite element AWP code. By combining innovative octree-based mesh representation with the highly parallel finite-element (FE) Hercules code, CMU researchers demonstrated scalability on thousands of processors at an execution rate greater than 1 teraflop (TF) sustained for over four hours.

CyberShake Platform

CyberShake is a capacity-computing platform for executing and managing the large number of Pathway 2 simulations needed to construct physics-based PSHA maps. CME has built capacity computing through a grid-based computing architecture, initially using the NMI software stack and Condor-pool technology to speed up Pathway 1 computations from days to hours. In the last year, we have demonstrated the feasibility of calculating simulation-derived seismic hazard curves for sites in Southern California that are based on full 3D waveform modeling. This platform uses large-scale scientific workflows based on Pegasus and DAGMan.

DynaShake Platform

DynaShake is a newly developed capacity-computing platform designed to enable high-performance computation of large suites of high-resolution dynamic fault rupture (DFR) simulations. To create this Pathway 3 capability, the SDSU group, led by S. Day, has integrated into the Olsen AWP code a highly scalable DFR code based on the accurate, verified staggered-grid, split-node (SGSN) scheme. The resulting code is limited to planar faults, but it can accommodate complex friction models, which is key to the physics we seek to understand. DynaShake has friction modules for both linear and nonlinear slip-dependent frictions laws, as well as prototypes of rate- and state-dependent friction modules, including a generalized formulation with strong velocity weakening.

BroadBand Platform

The Broadband platform is designed to calculate low frequency deterministic 2-D and 3-D waveforms and to combine those waveforms with High Frequency Stochastic Models (HFS) to produce synthetic seismograms with high frequency content. Currently, the BroadBand Platform is in prototype mode and it includes multiple codes for both the deterministic and stochastic calculations.

Full Three Dimensional Tomography (F3DT)

Full 3D Tomography (F3DT) is a new capacity-computing platform for executing Pathway 4 (inverse) calculations. In F3DT, the starting model as well as the model perturbation is 3D and the sensitivity (Fréchet) kernels are computed using numerical simulations that incorporate the full physics of 3D wave propagation. F3DT can account for the nonlinearity of structural inverse problem through iteration, and it provides the means for updating the CVMs using seismic observations—an important validation step for predictive ground motion simulations.

Earthworks Platform

The Earthworks Platform is a web portal that is designed to allow users to easily configure AWP simulations and to produce a well defined set of data products including ground motion maps, synthetic seismograms, and animations. This platform also supports verification and validation of simulation codes by allowing researchers to easily re-run verification and validation problems.

PetaShake Platform

The PetaShake Platform is a proposed platform that can scale up to 10,000+ and more processors. If the highly scalable PetaShake codes can be developed, these highly scalable elements of the PetaShake platform can be applied to the TeraShake, CyberShake, F3DT and DynaShake platforms.

Summary of Scientific Advancements Supported by SCEC/CME

The SCEC modeling groups have been actively developing new capabilities for the SCEC platforms as well as running large scale simulations. In the following sections, we summarize some of the science activities and results of the SCEC CME and PetaSHA groups.

OpenSHA Project

The OpenSHA platform has been extensively validated and is now fully operational, and its use of grid-based workflows puts capability-computing power at the disposal of PSHA researchers. An OpenSHA study of scenario ruptures on the Puente Hills blind thrust, located beneath downtown Los Angeles, estimated that such an event could result in up to 18,000 lives lost and $250 billion in direct economic losses (Figures 37 and 38).

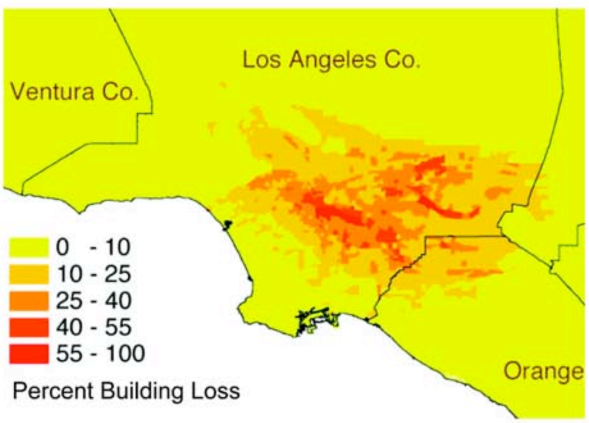


Fig. 8. Map of building loss in Los Angeles from a M7.1 simulated earthquake on the Puente Hills blind thrust, calculated by coupling the OpenSHA platform to FEMA's HAZUS loss-estimation software [*37*]. Note the extensive areas where losses are estimated to exceed 40%. PetaSHA-2 will allow physics-based PSHA to be used in scenario-based risk analyses.

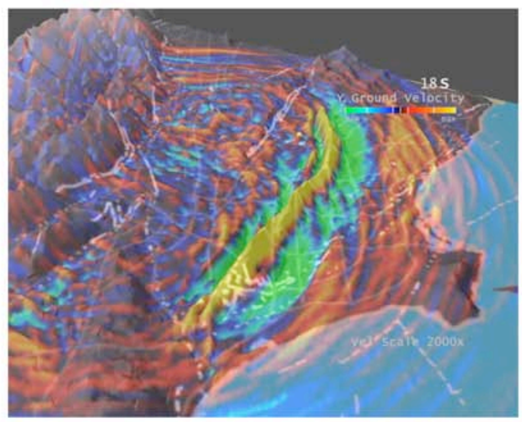


Fig. 9. Snapshot looking east across Los Angeles of N-S ground velocity from a broadband (0-10 Hz) simulation of a M7.1 earthquake on the Puente Hills blind thrust. Snapshot is 18 s after origin time and shows large surface waves propagating through the low-velocity sediments of the LA basin. The BroadBand platform of PetaSHA-2 will allow revisions of Fig. 8 using such simulations.

Figures 37 and 38 above

TeraShake Project

A San Diego-based CME team led by K. Olsen (SDSU) tackled large-scale simulations of earthquakes on a southern segment of the San Andreas fault capable of producing a M7.7 earthquake. The southernmost portion of this segment has not ruptured since ~1690, and its conditional 30-yr probability based on paleoseismic data is high. Ground motions were computed on a regional scale up to 0.5 Hz using the SCEC CVM3.0, represented on a 1.8 billion node grid.

TeraShake-1 (Figure 39 left panel), which was run at SDSC, produced new insights into how *rupture directivity*—the tendency for energy to be focused in the direction of rupture propagation—couples to *sedimentary basin effects*, which include ground-motion amplification by soft sediments, constructive interference among the various types of basin waves, and waveguide effects. In particular, the simulations showed how the chain of sedimentary basins between San Bernardino and downtown Los Angeles form an effective waveguide that channels surface waves along the southern edge of the Transverse Ranges. Earthquakes scenarios with northwestward rupture, in which the guided surface wave is efficiently excited, produced unusually high long-period ground motions over much of the greater Los Angeles region, including intense, localized amplitude modulations arising from variations in waveguide cross-section.

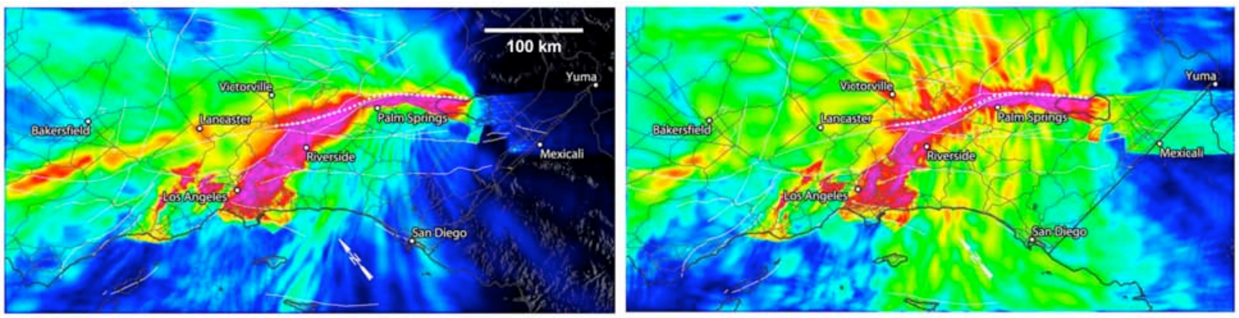


Fig. 1. Maps of Southern California comparing 3-s spectral accelerations from two TeraShake simulations. The M7.7 rupture propagates NW-SE on the same 200-km section (dashed) of the San Andreas fault. Left panel is a TeraShake-1 run that used a kinematic source model [*1*]; right panel is a TeraShake-2 run that used a dynamic source model [2]. Both predict strong ground motions (red colors) in the Los Angeles basin from energy funneling through sedimentary basins south of the San Bernardino and San Gabriel mountains. Amplitudes of the less coherent (and more realistic) dynamic model are lower by 2-3 in the LA Basin and show "sun burst" patterns, associated with rapid variations in rupture speed and direction.

Figure 39 above

In TeraShake-2 (Figure 39 right panel), we extended these simulations from a kinematic fault rupture (*KFR*) model to a dynamic fault rupture (*DFR*) model using the P3/P2 decomposition described earlier. We have confirmed the waveguide effects, but have found that the amplitudes of the less coherent (and more realistic) *DFR* model are lower by factors of 2 to 3 in the LA Basin. The new *DFR* simulations show "sun burst" patterns outward from the fault, associated with rapid variations in rupture speed and direction.

The *ShakeOut* exercise exemplifies how the PetaSHA platforms are supporting earthquake risk reduction. The USGS initiated ShakeOut as part of the new Multi-Hazard Demonstration Project. Geologists defined a realistic M7.8 rupture scenario on the San Andreas. The OpenSHA platform was used to develop an initial ground motion map for the rupture, and the TeraShake platform was used to construct a common velocity model for the simulation region. The velocity model and TeraShake codes were validated by comparing synthetics with observed seismograms for small events in the region. Multiple teams are now using the TeraShake platform to simulate the scenario event out to 1Hz. The ShakeOut exercise will culminate with the SoCal-wide "Golden Guardian" disaster response exercise in Nov 2008, which will involve emergency managers at the federal, state and local levels.

The TeraShake platform has been the venue for many improvements in code parallelization, data management, and scientific visualization, and it has reduced the production time and the team size required for large-scale simulations. The excellent scaling of the Olsen and CMU *AWP* codes (Figure 40) on up to 40,960 processors have allowed the CME team to compete successfully for successively larger allocations of NSF computing resources. In March 2007, we received a 15.3 million SU allocation on TeraGrid machines (the largest ever by LRAC). We plan to evolve the TeraShake platform toward a petascale capability. This *PetaShake* capability-computing platform will be focused of our parallel proposal to OCI.

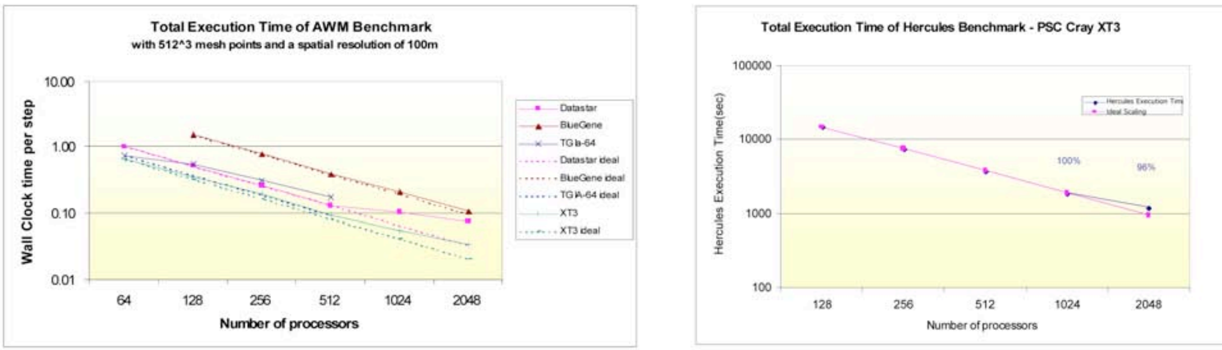


Fig. 10. The Olsen (left) and Hercules (right) *AWP* codes show efficient scaling on over 2000 TeraGrid processors. Benchmarking of the Olsen code on Blue Gene Watson has demonstrated up to 96% efficiency on over 40,000 processors [*46*].

Figure 40 above

CMU Hercules – Extending TeraShake to 1Hz

Over the last few years, members of the CMU Quake group have developed and implemented a new methodology for earthquake ground motion simulation within a system named Hercules. This system targets unstructured octree-based finite element PDE simulations running on multi-thousand processor supercomputers. This system was completed in time to be presented and demonstrated last November at Supercomputing 2006. All its simulation components, i.e., meshing, partitioning, solving and visualizing, are implemented on top of, and operate on, a unified parallel octree data structure. There is only one executable (MPI code) in which all the components are tightly coupled and execute on the same processors. The only input is a description of the material database and of the kinematic source; the output can be in the form of lightweight jpeg-formatted visualization frames generated as they are simulated at every visualization step, or as 4D (space-time) seismograms. The Quake group won the SC06 HPC Analytics Challenge for this end-to-end simulation system.

As part of the PetaSHA project, the group used Hercules to conduct both a TeraShake scenario earthquake, presented at the 2006 Fall Annual AGU Meeting, and, more recently, a ShakeOut scenario, which we used to verify our computational system with results generated by Rob Graves with a structured finite difference code. In the TeraShake scenario, they simulated an Mw7.7 earthquake on a portion of the San Andreas Fault in southern California over a volume of 600 km x 300 km x 80 km for a maximum frequency of 1 Hz and a minimum shear wave velocity of 200 m/s. This simulation, with 147 million nodes and 140 million elements, ran on 2048 processors of BigBen at the Pittsburgh Supercomputing Center. With time steps of 0.006 s, it took a total of 15 hrs 3 min to simulate 180 s of ground motion. Of this time, 39 min were needed to construct the mesh, 17 min to generate the source, and 14 hrs 7 min to solve the correponding initial-boundary value problem. The two simulation results provide a clear illustration of how ground motion simulations of large earthquakes can help gain a better understanding of the spatial distribution of ground motion during earthquakes, and how this ground motion is influenced by the presence of basins and the surrounding topography.

The ShakeOut scenario is a similar, though smaller, simulation of a different, Mw 7.8 earthquake, within the same general region in southern California. The maximum frequency is 0.5 Hz and the shear wave velocity is cropped at 500 m/s. One of the main objectives of this earthquake scenario was to be able to verify the simulation results of several codes for large earthquakes over extended regions. We have compared the Hercules simulated seismograms against Rob Graves calculated seismograms for the same scenario and the waveforms match very closely. To our knowledge, this is the first time that a comparison has been conducted for a large earthquake over such a large region, with this remarkable agreement.

DynaShake Platform Development

The PetaSHA group has initiated development of DynaShake, a computational platform to enable high-performance computation of large suites of high-resolution dynamic rupture simulations. The key step was our development and verification of a highly scalable dynamic fault rupture (DFR) code for high-performance simulations. DFR integrates the very accurate, well-verified Staggered-Grid Split Node (SGSN) scheme into the AWP-Olsen code. The rupture dynamics component is modularized such that this integration preserves the scalability of AWP-Olsen. The resulting code is unparalleled in its capability for simulating rupture in simple (Cartesian) geometries, can accommodate complex friction models, and serves as a baseline for verification of codes for geometrically complex ruptures. DFR has friction modules for both linear and nonlinear slip-dependent frictions laws, and we have working prototypes of rate- and state-dependent friction modules (classic slip and aging laws modified for low slip-speed regularization, as well as a generalized slip-law formulation with strong velocity weakening to simulate flash-heating of asperities). The latter required an implicit ODE solver based on backward differentiation for updating the coupled system (state variable, slip rate vector, fault traction vector), and has very high precision as verified by comparison with boundary integral solutions.

We have used DFR to simulate dynamic slip models for a 300 km long rupture of the southern San Andreas fault, which is the earthquake scenario prescribed for the USGS ShakeOut exercise. The ShakeOut scenario defines not only the rupture-surface and moment magnitude of the event, but also prescribes the final surface slip distribution resulting from the rupture. We developed a “slip-matching” technique for constraining initial (shear and normal) stress conditions in DFR simulations such that they conform to scenarios defined in this form. The slip-matching method iteratively performs kinematic and dynamic simulations at low resolution to find initial stress distributions that have stochastic irregularities compatible with seismological observations, satisfy frictional strength limits at shallow depth, are slip-matched to surface displacement scenarios, and rupture the full length of the specified scenario.

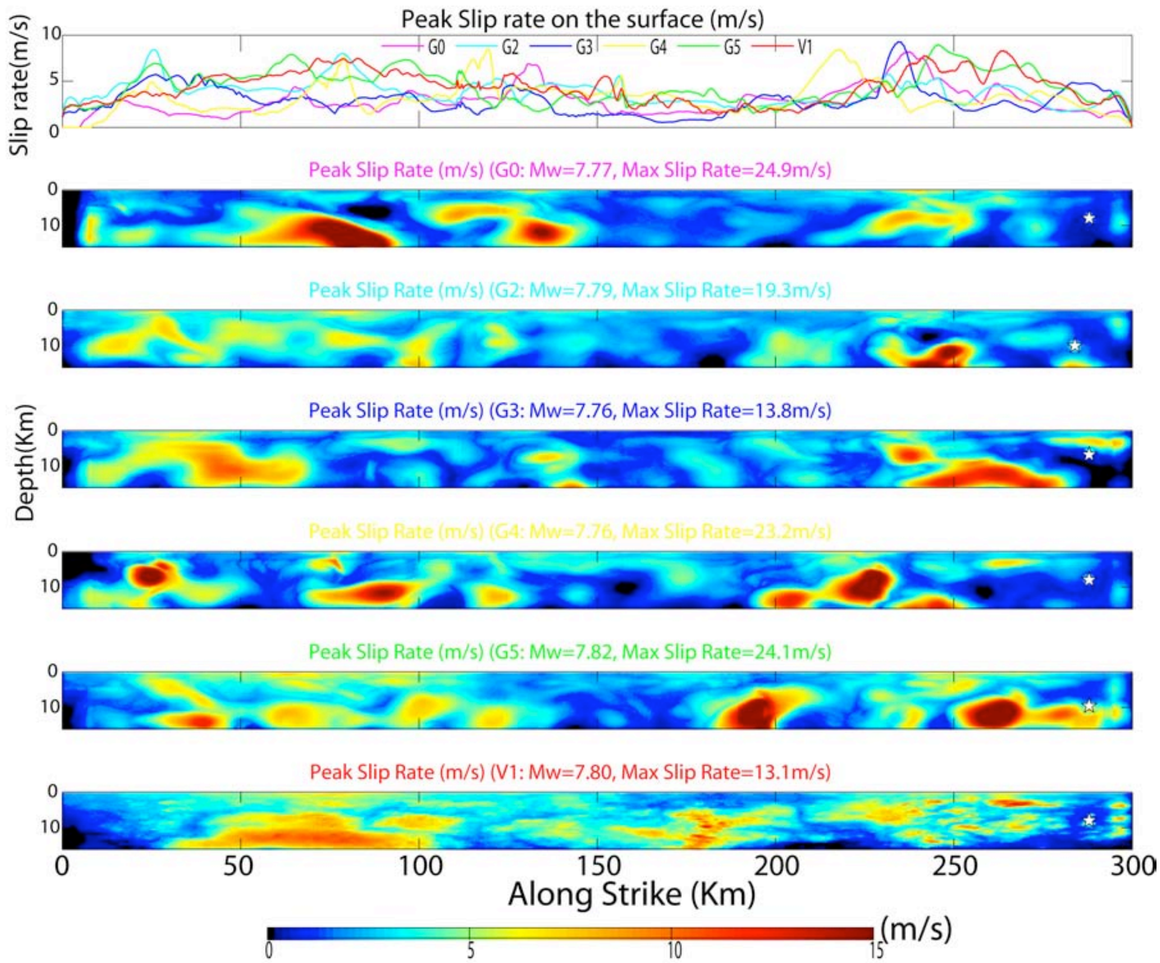


Figure 41: DynaShake dynamic rupture results showing slip matching technique.

Figure 41 shows preliminary results from DFR ShakeOut simulations, done using six different slip-matched initial stress distributions. Five of these (G0,G2,G3,G4,G5) are based upon a Gaussian model of stress irregularities, and the sixth (V1) is based upon a von Karman model. Figure 42 shows the final surface slip distributions, which are very similar and generally well-matched to the target (although, interestingly, dynamic normal stress perturbations induced by wavespeed contrasts across the fault have distorted the slip match near the northern extreme of some of the models). The corresponding slip-velocity distributions are very different form one another, however: a wide range of slip space-time histories prove consistent with the scenario definition. The maximum dynamic stress drops in these slip-matching models vary by nearly a factor of 3 (from ~23 to ~60 MPa), and it will be interesting to see how much variability in surface motion amplitude this variability in stress drop induces within the context of a single surface-slip scenario. The von Karman model (which has power-law behavior at large wavenumber) shows small-scale spatial fluctuations in slip that are more significant than in the Gaussian cases, and that model also evolves rupture fronts with small-wavelength structure not evident in the Gaussian cases. These consequences of stress irregularities may have significant implications for seismic directivity, and deserve further analysis using higher-resolution DFR simulations.

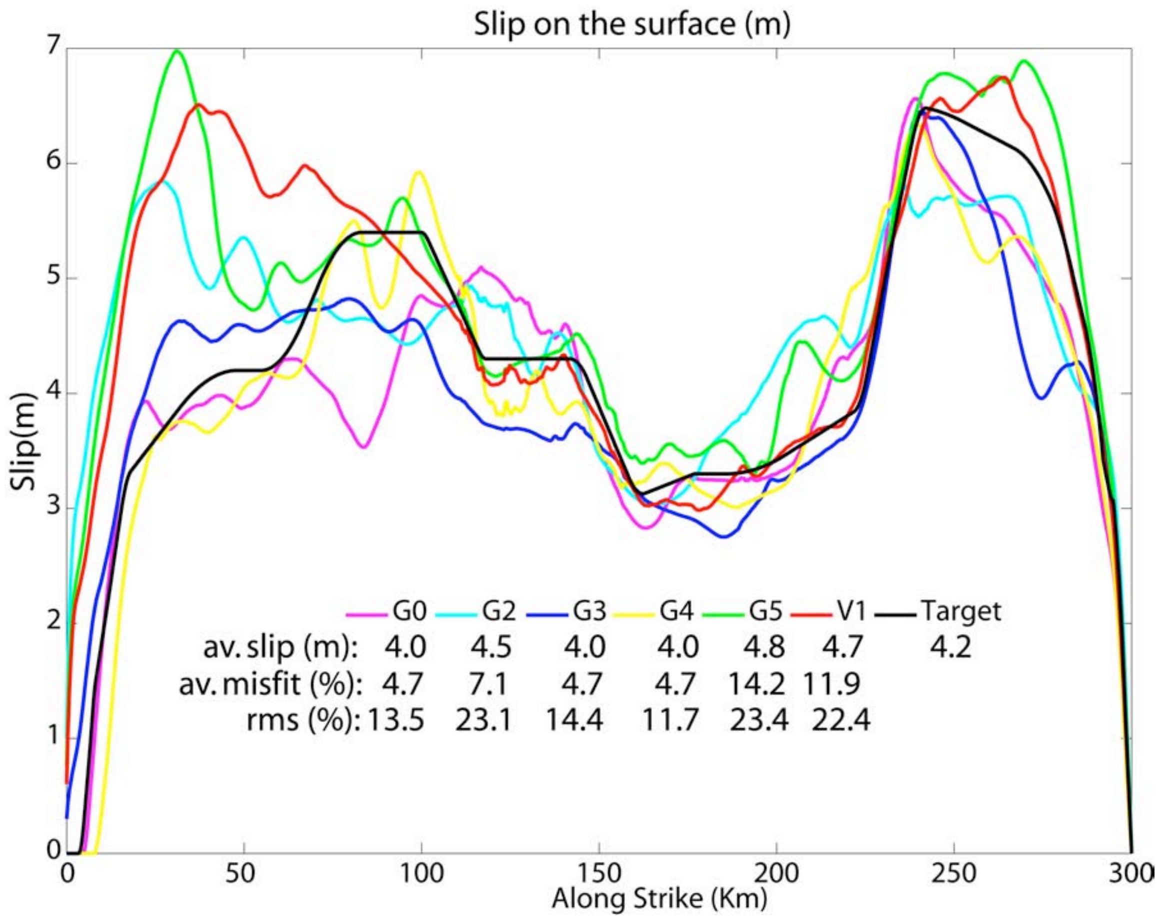


Figure 42

Cybershake

The CyberShake science team, led by R. Graves (URS), is developing CyberShake as a platform within PetaSHA cyberfacility. The current implementation of CyberShake samples ~13,000 distinct sources in the NSHMP-2002 *ERF* for Southern California. For each large (M > 6.5) source, the hypocenter, rupture rise-time and velocity distributions, and final slip distribution have been varied according to a pseudo-dynamic model, producing a total catalog of more than 100,000 *KFR*s. To make the calculations feasible on current hardware, the Olsen and Graves *AWP* codes have been modified and optimized to calculate "receiver Green tensors" (RGTs). Using seismic reciprocity, we can efficiently post-process the RGTs to synthesize a site's ground motions for the full suite of *KFR*s and, from this database, compute hazard curves for spectral accelerations below 0.5 Hz.

CyberShake promises to deliver new insights about how rupture directivity and sedimentary basin effects can modify hazard curves. The four examples shown in figure 43 are from a rock site (PAS) and three soft-soil sites (USC, LBP, WNGC) in the Los Angeles basin region (Figure 43). At Pasadena, the CyberShake estimate is close to the conventional approach for return periods down to about 10^{-3}/yr. This is consistent with expectations, since Pasadena has no basin effect and the potential for directivity from nearby sources is mitigated by the low slip rates (e.g. on the Sierra Madre and Raymond faults). The basin sites exhibit much higher hazard levels, with the largest difference occurring for Whittier Narrows. The higher probabilities obtained by CyberShake at these sites are due to a combination of basin response and rupture directivity effects, as verified by TeraShake results for the Whittier Narrows site.

CyberShake opens the door to a novel method for validating PSHA simulations based on the mapping of "precariously balanced rocks", which can be used to set quantitative bounds on the intensity of seismic shaking integrated over intervals long enough (>10,000 yr) to sample a complete *ERF*. Because precarious rocks are located at hard-rock sites and not subject to basin effects, they may set useful bounds on poorly known source radiation parameters—in particular, rupture directivity. For example, groups of precarious rocks have been mapped by J. Brune near extensional step-overs on SoCal strike-slip faults. Based on the TeraShake simulations, he speculates that the shaking at these sites is anomalously low because the fault ruptures tend to propagate *away* from extensional step-overs. We will combine broadband CyberShake simulations with mapping of precarious rocks to test models of source directivity and evaluate constraints on its predictability.

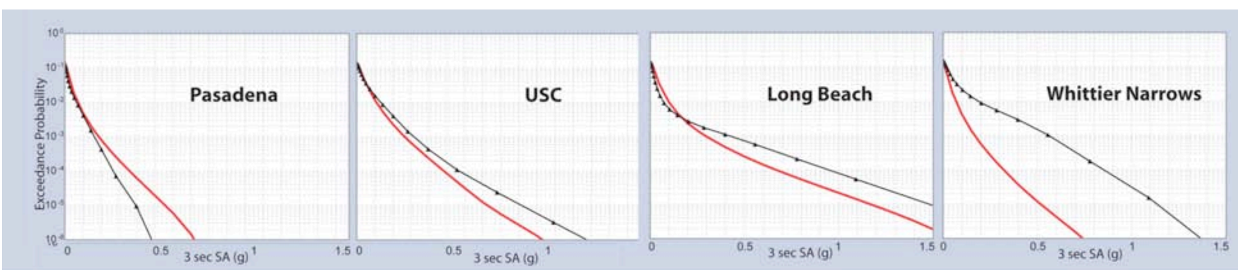


Fig. 11. Plots of the probability of exceedance against shaking intensity (*Sa* at 0.3 Hz) for four sites in the LA region. Black curves are calculated by CyberShake from 100,000+ simulated earthquakes. Red curves are a conventional PSHA calculation using the Abrahamson & Silva [*50*] attenuation relationship, truncated at the 3-sigma level consistent with NSMP-2002. The physics-based curves for the 3 basin sites lie well above the empirical ones, implying that basin effects severely amplify the hazard.

Figure 43 above

Full 3D Tomography (F3DT)

SCEC researchers have been developing F3DT algorithms that fall into two classes: the *adjoint wavefield* (AW) formulation and the *scattering integral* (SI) formulation. The two are closely related, but their relative efficiency depends on the problem geometry, particularly on the ratio of sources to receivers. The SI method, which computes Fréchet kernels for individual measurements by convolving source wavefields with RGTs, is computationally more efficient than the AW method in regional waveform tomography using large sets of natural sources, although it requires more storage.

The USC group, led by Po Chen (now at Lamont), has successfully applied a scattering-integral (SI) formulation of F3DT to improve CVM3.0 in the Los Angeles region. They have inverted time- and frequency-localized measurements of waveform differences to obtain a revised 3D model, LAF3D, that provides substantially better fit to the observed waveform data than the 3D starting model. To our knowledge, this study is the first successful application of F3DT in structural seismology.

SCEC Earthworks Science Gateway and Visualization Portal

A PetaSHA working group is converting the SCEC/CME computational testbed into a portlet-based system. The current SCEC computational testbed allows users to define, and run pathway 2 simulations. The web portal under development, called the SCEC Earthworks System, uses a JSR-168 compliant portlet system (Gridsphere) to allow users to run pathway 2 simulations. The system uses Pathway 2 codes that have been integrated including Kim Olsen's code, Robert Grave's code, and the Hercules code. The codes will be validated through the use of SCEC validation simulations. The system is constructed so that simulations of earthquakes in southern California can be executed immediately after they occur and so that data products will be produced. The system will utilize the SCEC grid-based workflow system to access the required HPC systems. Simulations with results of long term interests will store their results in the SRB.

The SCEC Earthworks Science Gateway (Figure 44) is a system that will allow non-traditional users of supercomputers to run earthquake simulations on the TeraGrid. This SCEC Earthworks Project is an integration effort that pulls together elements from both TeraShake and CyberShake. SCEC Earthworks uses the TeraShake AWM software as its basic code. It also uses the same workflow tools (Pegasus and the VDS) as the CyberShake system. It also uses the Storage Resource Broker at SDSC. There is also a collaborative effort with SDSC Visualization Services to produce animation from SCEC Earthworks data.

The SCEC Earthworks portal has been prototyped and has run end to end AWM earthquake wave propagation simulations that include the user configuration of the simulation through a grid portal, the creation of DAX's that describe the computational steps, the execution of the codes necessary to prepare and run the simulation, the post processing to create specific data sets, and the registration of the resulting data into the SRB.

An important element of this work is the utilization of the SCEC TeraShake code as the "community code." But integrating the TeraShake code into Earthworks, we have expanding its usage within SCEC. The Earthworks group has performed modifications to the TeraShake code to support its use in workflows. This involves removing hard-coded file names which are then passed on the command line. The code changes to the TeraShake AWM code are coordinated between SDSC and SCEC through the use of a CVS system.

The SCEC Earthworks group has also collaborated with the SDSC Visualization Services group on creating a Visualization Services Request. When the Earthwork system has created a new data set for which we want an animation, we will send the SDSC Visualization Service group a service request which indicates the SRB storage location of the data we want processed.

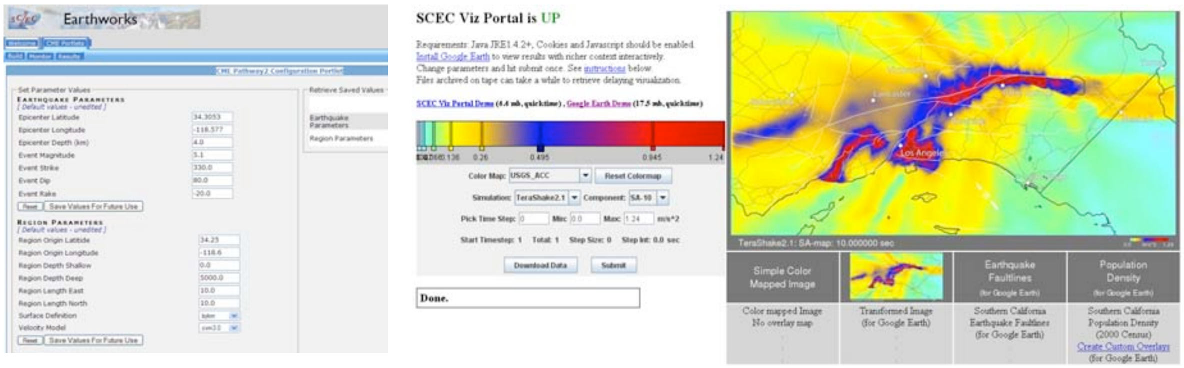


Figure 44:The SCEC Earthworks Science gateway, on the left, provides access to the TeraShake AWP platform, and the SCEC Viz portal interface, center and right, provides access to Visualization tools, visualization cluster, and SCEC AWP and DFR simulations results

Summary

The SCEC CME and PetaSHA special projects continue to be a valuable addition to the SCEC science plan. These special projects have changed how SCEC researchers perform their simulation-based research by providing opportunities to collaborate with computer scientists on large-scale and challenging projects. Through these projects, SCEC is now able to run on a larger scale than ever before possible. These simulations-based special projects are closely coupled to the SCEC science plan. This close coupling provides helps to advance the core SCEC science program and has helped SCEC researchers develop a better understanding of seismic hazards in Southern California.

Earthquake Engineering Implementation Interface

SCEC's research initiatives at the earthquake engineering implementation interface include participation in the Next Generation Attenuation (NGA) Program, in ground motion time histories for performance-based seismic engineering, and in end-to-end simulations from earthquake rupture to building response (rupture-to-rafters) for several projects. These initiatives perform research into the characteristics of earthquakes and the ground motions that they cause, and apply that research to the development of seismic design criteria for buildings and other structures, including the development of seismic provisions of building codes. The importance of SCEC's strong motion simulation capabilities for these projects stems from the sparsity of recorded ground motion time histories that represent the conditions (proximity to large earthquakes) that control the seismic design of buildings in coastal California, and the fact that response spectral ground motion prediction models for these conditions are based largely on extrapolation of recorded motions to larger magnitudes and closer distances.

Some of the research described below was funded by the NSF funded project: Implementation of SCEC Research for Seismic Risk Reduction, Award CMS-0409705 10/04 -9/07, $821,000. P.I.: Tom Jordan, USC. SCEC has proposed further collaborative research in conjunction with the earthquake engineering research community, including Ground Motions from Large Southern San Andreas Earthquakes and Their Impacts on Tall Buildings in Los Angeles, submitted jointly by SCEC and PEER to NSF CMMI & EAR, and NEESR-SG: Integrated Rupture to Response Simulations Using Hybrid Testing of Geo-structural Systems, submitted by CUREE and SCEC to NEESR.

Participation in the PEER-Lifelines Next Generation Attenuation (NGA) Project.

SCEC is a co-sponsor and co-participant with PEER and the USGS in the NGA Project, whose objective is to develop a new set of response spectral ground motion prediction models for use in seismic hazard analysis (peer.berkeley.edu/lifelines/NGA.html). Current ground motion prediction models are based mainly on recorded strong motions, and so are poorly constrained for large magnitudes and close distances. SCEC's role in this project, sponsored by funding from NSF - CMS & EAR and the California Earthquake Authority (CEA), involves the use of broadband strong motion simulation to generate ground motion time histories for use, in conjunction with recorded ground motions, in the development of ground motion attenuation relations that are better constrained, especially for large magnitudes and close distances, and are based on an improved understanding of the relationship between earthquake source and strong ground motion characteristics.

We used rupture dynamic modeling (Pitarka and Dalguer, 2003; Dalguer and Day, 2005, 2006) to shed light on the physics of why surface faulting earthquakes have weaker ground motions than those of buried faulting (Somerville, 2003). We showed that with increasing weakness, the shallow zone is increasingly effective at arresting the upward propagation of rupture to the surface, reducing the slip velocity on the fault, and reducing the strength of the ground motion, as shown in Figure 45 (Somerville and Pitarka, 2006). The NGA models predict ground motions that are significantly lower than those of models in current use, due to part to inclusion of ground motions recorded during recent large surface faulting earthquakes, including the Mw 7.6 1999 Chi-Chi, Taiwan, Mw 7.4

1999 Kocaeli, Turkey and Mw 7.9 2002 Denali, Alaska earthquakes.

SCEC also strengthened its capabilities in broadband simulation of strong ground motion for use in the next phase of the NGA Project. We developed additional alternative broadband strong motion simulation procedures, verified them using simple test cases, and are validating them against strong motion recordings (Lavalee and Archuleta, 2005; Liu et al., 2006). We also initiated development of a platform for broadband simulation that allows users other than the developers of the software modules to use them in verification exercises, validation against recorded data, and simulations of scenario earthquakes. This platform will provide objectivity and transparency in the testing and application of broadband simulation procedures, enhancing confidence in their use in earthquake engineering.

End-to-End Simulation of Ground-Motion and Structural Simulations for Scenario Earthquakes in Los Angeles (Rupture to Rafters).

Current procedures for estimating earthquake damage and losses involve characterizing the ground motion level throughout a region using simple ground motion parameters such as intensity, peak acceleration or response spectral acceleration, and then estimating the losses for individual structures using simple correlations between ground motion level and damage. A much more rigorous and realistic procedure is to calculate the full ground motion wave field throughout the region and input it into nonlinear time history analysis of structural response models of the buildings and infrastructure that the region contains. This integrated simulation approach enables the realistic analysis of the nonlinear response of structures throughout the region in a manner that fully integrates earthquake science and earthquake engineering.

In a project funded by the CEA, SCEC participated in analysis of the response of wood frame buildings throughout the greater Los Angeles region to scenario earthquakes on the Puente Hills Blind Thrust. In a project funded by NSF CMS & EAR, SCEC participated in analysis of the response of steel frame buildings throughout the greater Los Angeles region to a magnitude 7.9 earthquake on the San Andreas fault. SCEC also performed end-to-end simulations to assess the potential performance, including collapse, of moderate rise steel moment-frame buildings during earthquakes on the Puente Hills blind thrust, a large, north-dipping blind fault system that underlies the densely urbanized Los Angeles metropolitan region, discovered by SCEC scientists (Shaw and Shearer, 1999; Shaw et al., 2002). Broadband ground motion simulations of large earthquakes on the Puente Hills thrust were performed by Graves and Somerville al. (2006) using the SCEC Community Velocity Model. The responses of 20- and 6-story steel frame buildings with perfect and brittle welds throughout Los Angeles were simulated using the seismic nonlinear structural simulation program, Frame 2-d, developed by Hall (1997). Building response simulations were done for each of 10 scenario earthquakes, including events on the Puente Hills Blind Thrust and events previously simulated by SCEC, and the results were aggregated into composite maps of maximum interstory drift ratio (Heaton et al., 2006; Olsen et al., 2006a,b; Figure 46). This study concluded that most sites within the Los Angeles basin could be shaken by ground motions that could cause severe deformation of 20-story steel frame buildings, especially for steel frame buildings with brittle welds. Preliminary analyses of the response of these buildings to a scenario earthquake on the Southern San Andreas fault were also done.

Ground-Motion Time Histories for Performance-Based Earthquake Engineering.

The west coast of the United States is undergoing an unprecedented boom in the construction of tall buildings. The objective of the Tall Buildings Initiative is to support of the development and application of alternative design concepts for the seismic design of tall buildings, for which current building code procedures are unsuitable. This project is lead by the Pacific Earthquake Engineering Research Center (PEER) and involves many other organizations involved in earthquake science and engineering research (SCEC, USGS), practice (Structual Engineers Association of California, Los Angeles Tall Buildings Seismic Design Council), code development (Applied Technology Council, FEMA), and code implementation (Los Angeles Department of Building Inspection, San Francisco Department of Building and Safety). SCEC's role is to provide broadband simulations of strong ground motion time histories of the large, nearby earthquakes that control the seismic design of tall buildings in Los Angeles and San Francisco, and for which recorded ground motions are sparse. Ground motion time histories are required for the nonlinear building response analyses used in the performance-based seismic engineering approaches that form the basis of the alternative design procedures.

SCEC organized and participated in the SCEC/PEER Roundtable Discussion on Impact of Large Earthquakes on Tall Buildings in Los Angeles. The purpose of the Roundtable was to discuss the characteristics of ground motions in Los Angeles from large earthquakes, their potential impacts on tall buildings, methods for controlling collapse and damage, and implications for design practitioners. Participants in the Roundtable included SCEC strong motion seismologists, and structural engineers involved in research (PEER), practice, and building code development. Before the Roundtable, Robert Graves provides time histories for a scenario earthquake on the Puente Hills Blind Thrust fault beneath Los Angeles (Graves and Somerville, 2006). These time histories were used as inputs into analyses of the strength and capacity of model structures (Naeim and Graves, 2006), which concluded that tall buildings may be less vulnerable to moderate level ground motions than other buildings, and that all categories of buildings are vulnerable to the severe level ground motions.

SCEC planned and participated in a workshop on the selection and scaling of ground motion time histories at the 2005 NEES Annual Meeting, participated in the 2006 LATBSDC Meeting (Somerville et al., 2006), and provided time histories for a parametric study of the impact of ground-motion variability on structural response for a 7-story frame tested at UCSD.

Reports

Reports to NSF

#1. Implementation of SCEC Research for Seismic Risk Reduction, June 30, 2005

#2. Implementation of SCEC Research for Seismic Risk Reduction, June 30, 2006

Reports to the California Earthquake Authority (CEA)

#2. Science needs of NGA Modelers, Feb 28, 2006

#3. Broadband ground motion simulation for scenario ruptures on the Puente Hills fault, Feb 28, 2006

#5. Physical explanation of changes in NGA models, August 31, 2006

#6. Index woodframe houses and their response to Puente Hills scenario earthquakes, August 31, 2006

#7. Participate in Phase NGA-H of the Next Generation Attenuation (NGA) Project, February 28, 2007

#8. Index woodframe houses and their response to Puente Hills scenario earthquakes, February 28, 2007

#9. Index woodframe houses and their response to Puente Hills scenario earthquakes, June 30, 2007

Reports to the Tall Buildings Initiative Project

Development of Criteria for the Seismic Design and Analysis of Tall Buildings

#1. Simulated broadband ground motion time histories of Puente Hills scenario earthquakes for the TBI project, December 12, 2006

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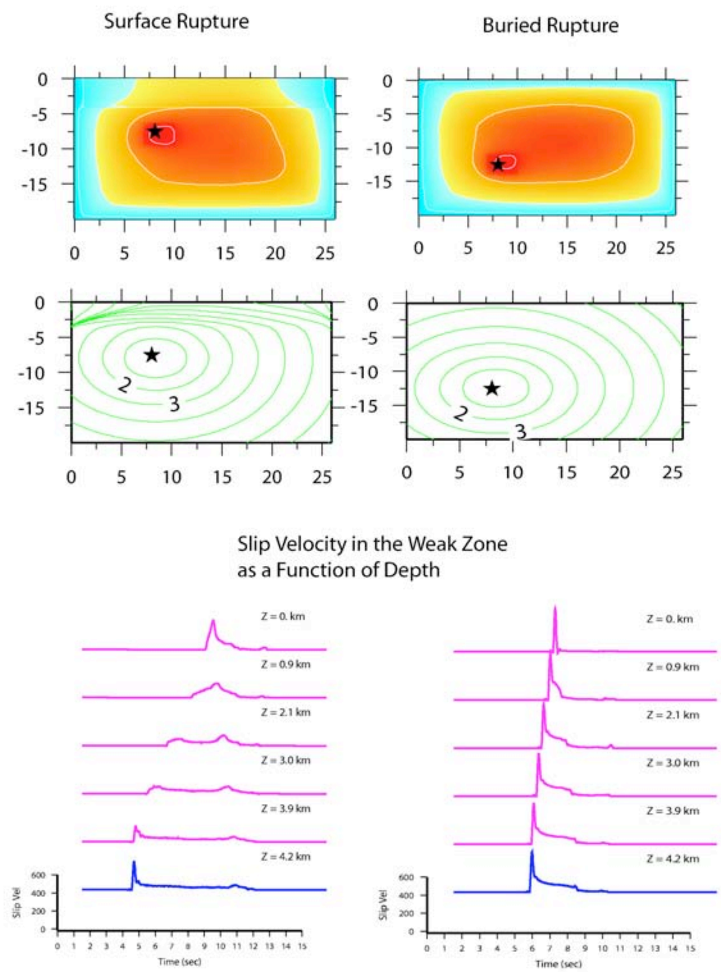

Figure 45. Comparison of slip functions on the fault for surface (shallow stress drop = 1Mpa, left) and buried rupture (right), showing much larger slip velocities on the fault for the buried rupture case.

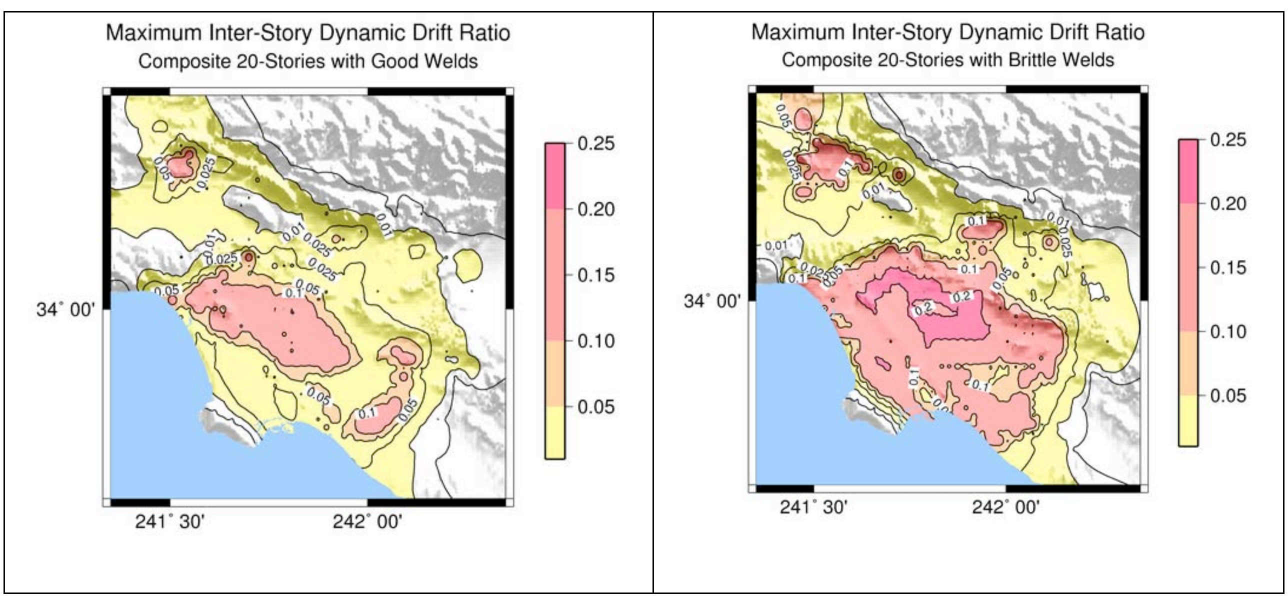

Figure 46. Maximum interstory dynamic drift ratio from ten scenario earthquakes for 20 story steel frame buildings with good (left) and brittle (right) welds. Source: Olsen et al., 2006.

Borderland Working Group

The California Continental Borderland offshore of southern California is one of the most active continental margins of the late Cenozoic in the world. The region experienced significant elements of Paleogene subduction and Neogene extension, in addition to accommodating major strike-slip components associated with the evolving Pacific-North American (NAM) transform system. The Borderland was the locus of Pacific-NAM plate motion in southern California for about 70% of its tectonic history (from ~19 Ma to ~6 Ma), and recent GPS and VLBI data suggest that as much as 20% of the current plate boundary motion may still be located offshore. This has resulted in both mature and relatively young fault structures offshore that pose a serious but as yet unresolved seismic and possible tsunami hazard to large coastal populations of southern California. Thus, understanding the tectonic evolution of the plate boundary and the current tectonic architecture of the San Andreas fault system, as well as the tectonic history and seismic hazards of southern California necessarily requires a fundamental understanding of the offshore California Borderland.

Because of its significance, SCEC created the Borderland Working Group in June 2002. Its purpose was to focus and integrate research activities within the offshore Continental Borderland that relate to the scientific mission and objectives of SCEC. This includes the coordination of cooperative and collaborative research projects, helping to assess, archive and analyze existing offshore geologic and geophysical data, and helping to plan new research activities including future experiments within the Continental Borderland. An extended white paper on the initial objectives, goals, and research priorities of the Borderland Working Group was developed (http://www.scec.org/borderland) and is based largely on the results of the major Borderland Initiative Workshop held in March 2002 on Santa Catalina Island.

Major Achievements

Although SCEC's capabilities to conduct offshore research were severely limited, the Borderland Working Group was still able to promote and conduct a number of regional studies and collaborations, primarily through sponsoring workshops, expanding access and availability of critical offshore datasets, and leveraging resources from other agencies. For example, in June 2003, a workshop was held to develop a coordinated, integrated approach for the study of Borderland continental dynamics. The Borderland represents an ideal natural laboratory to investigate many aspects of continental deformation. Most of these are related to the general question of: *How does an oblique continental transform system initiate and evolve?* Four major science issues were identified:

- What happens when a spreading ridge obliquely subducts and initiates forearc rifting? Why is the Borderland offshore Southern California different from Northern California?
- How is mantle flow distributed along a continental transform boundary? Is plate boundary shear distributed or discrete, and are there differences in how the lower crust and upper mantle behave?
- What drives the large-scale rotation of the western Transverse Ranges Province? Is it driven from below by basal tractions, or from the sides?
- How does oblique continental rifting initiate and develop? Did continental rifting in the Borderland progress to seafloor spreading? How do high- and low-angle faults interact to accommodate oblique finite strain?

There are—of course—distinct advantages to working in the Continental Borderland, not the least of which is that much of it is underwater. This means that it is generally an area of ***deposition***, not erosion, so much of the deformation is preserved and a detailed syntectonic stratigraphic record is available to assess dates and rates of active continental deformation. Because it is underwater, high-resolution marine geophysical techniques can be used to image and evaluate this structure, stratigraphy, and tectonic geomorphology. Moreover, many of the most important scientific issues regarding active faults ***onshore*** in southern California also have analogs ***offshore*** in the Borderland where they are more easily imaged and evaluated in 3D. This includes such processes as strain partitioning, the interaction between fault sets of different orientation, and fault reactivation under different stress or strain regimes. And finally, the recent availability of extensive grids of existing, once-proprietary high-quality industry seismic reflection data provide substantial subsurface imaging capability in many areas (**Figure 47**).

A major accomplishment of the Borderland Working Group was, in fact, this successful transfer of these high-quality, proprietary multichannel seismic (MCS) reflection data—collected by the industry for hydrocarbon exploration—to the public domain. These data, including digital basemaps, navigation files and initial datasets are now available from the USGS National Archive of Marine Seismic Surveys (http://walrus.wr.usgs.gov/NAMSS) [*Childs and Hart*, 2004](**Figure 1**). These data represent an invaluable community resource tool. When correlated with well data and seismicity, these data can be used to map 3D reference horizons and fault surfaces to seismogenic depths, and provide accurate, quantifiable 3D images of subsurface fault geometry, basin development and finite deformation. With these and other high-resolution data sets in hand, substantial progress can be made in investigating the active deformation and hazard potential of the offshore Continental Borderland.

Figure 47. Screen capture from USGS National Archive of Marine Seismic Surveys (NAMSS) website (http://walrus.wr.usgs.gov/NAMSS/) showing thumbnail basemaps of some of the industry (WesternGeco) multichannel seismic reflection data (including digital navigation and seismic data files) now available along the Western United States [Childs and Hart, 2004].

Using these seismic data, together with other datasets collected by SCEC, USGS, NSF, NOAA and NURP that included additional MCS, refraction, gravity, magnetic, high-resolution multibeam bathymetry, seafloor geology, and offshore well data, various investigators were able to conduct several major studies of Borderland structure [*Miller*, 2002; *Fisher et al.*, 2003;

Nazareth and Clayton, 2003; *Baher et al.*, 2005], active fault systems [*Legg et al.*, 2004a; *Fisher et al.*, 2004, 2005a; *Sorlien et al.*, 2006], and tsunami potential [*Borrero et al.*, 2004; *Fisher et al.*, 2005b]. These investigations led to several major discoveries, some of which are discussed below.

Based on multibeam bathymetry, seismic reflection, gravity, magnetic and seafloor geology data, several large, enigmatic crater structures were discovered in the offshore Inner California Borderland (e.g., **Figure 48**) [*Legg et al.*, 2004b]. The origin of these submarine craters is still somewhat of a mystery as they exhibit in some respects (but not all) the expected geology, geomorphology, internal structure or geophysical signatures of either resurgent caldera, impact structures, or exposed plutons. Given their location and tectonic setting though, these features likely represent the largest previously undiscovered caldera complex in Western North America, and the first to be discovered in a submarine setting. Their discovery sheds new light on the timing and development of volcanic structures associated with continental rifting and the cumulative offset of subsequent strike-slip faults.

Another important discovery derived from the analysis of active fault systems in Santa Monica Bay and offshore of Palos Verdes Peninsula [*Sorlien et al.,* 2005; 2006]. This included investigation of the Palos Verdes, San Pedro Basin and San Pedro Escarpment faults of the inner Borderland that interact with and terminate against the more east-west-striking, north-dipping Malibu Coast and Santa Monica-Dume faults. This work led to the identification and mapping of the very large Palos Verdes anticlinorium as a single, fault-related fold structure (**Figure 49**). The subsurface fault responsible for this enormous feature may be the offshore extension of the active Compton blind thrust ramp beneath the Los Angeles basin. If so, then this represents a major increase in the seismic hazard potential to the Los Angeles area, based on the presence and proximity of this very large structure.

In a major collaborative, multidisciplinary study in Santa Barbara Basin, researchers used industry MCS, high-resolution seismic reflection and the USGS towed chirp system to map the 3D structure and outcrop stratigraphy along the Mid-Channel Trend associated with the active offshore Oak Ridge fault [*Nicholson et al.,* 2006]. The older stratigraphic sequences were then sampled by piston core. This produced the oldest, highest-resolution marine records of global climate change yet recovered from the world's oceans. This project also helped quantify patterns and rates of offshore late-Quaternary faulting and folding in the Santa Barbara Channel.

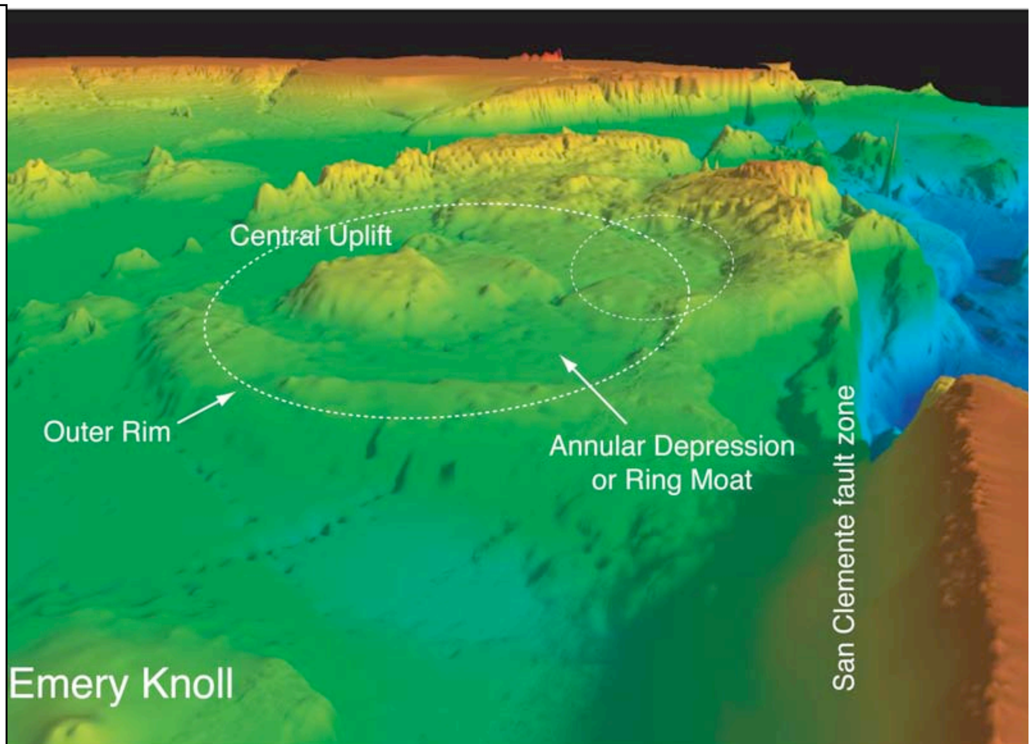

Figure 48. Oblique 3D view of shaded bathymetry looking southeast across Catalina Crater [Legg et al., 2004b]. Crater morphology, including central uplift, ring moat, and raised outer rim (large dashed circle), resembles that of a resurgent caldera or complex oblique impact structure. Possible secondary crater structure overlaps the southwest rim (small dashed circle).

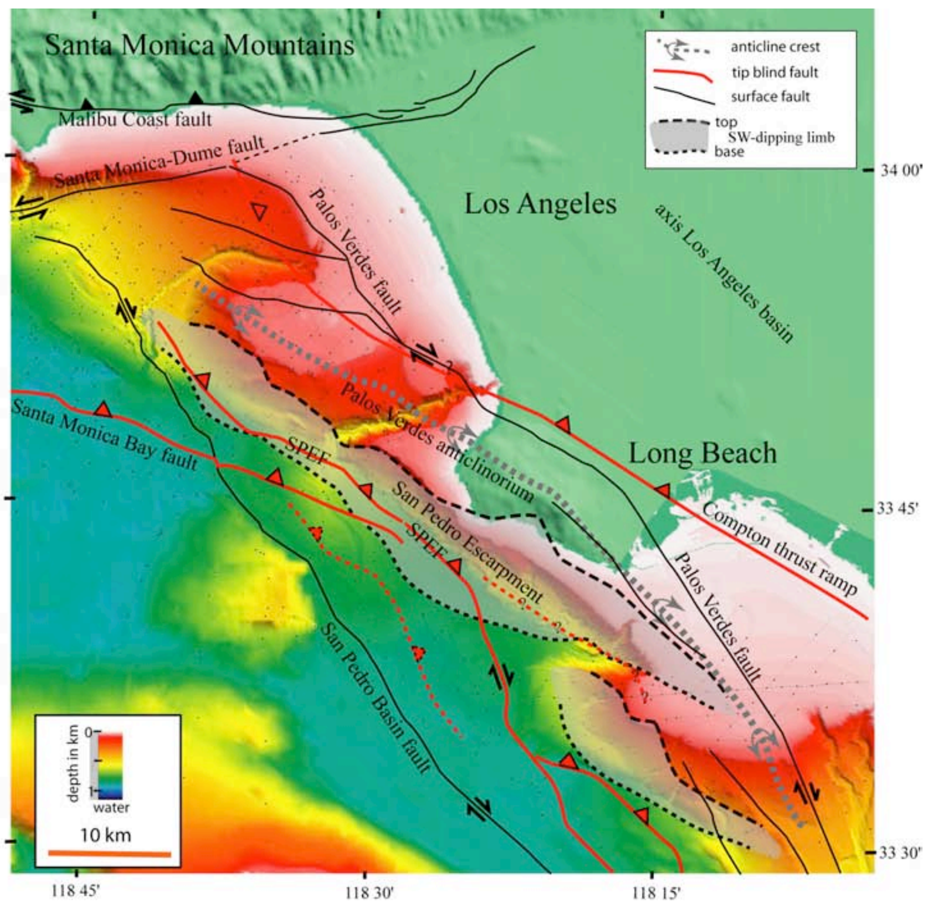

Figure 49. Map showing the Palos Verdes anticlinorium [Sorlien et al., 2005; 2006], a major regional fold structure, and its relation to the active underlying blind faults (red lines represent fault tips) that are driving this deformation. In this model, the Palos Verdes anticlinorium represents the offshore extension of the active Compton thrust ramp beneath the Los Angeles basin. Much of the uplift of the Palos Verdes Peninsula is then just a part of a much broader, more regional uplift associated with the Palos Verdes anticlinorium.

Several of these Borderland projects relied extensively on the industry MCS data available from NAMSS to regionally map both stratigraphic reference horizons and the geometry of active subsurface faults in 3D. This provided new and improved representations of active offshore faults to the SCEC Community Fault Model, as well as a quantitative means of estimating the cumulative finite strain absorbed by faulting and folding since deposition of the reference horizon—information crucial to SCEC's evaluation of crustal deformation rates, offshore hazards, and fault system dynamics.

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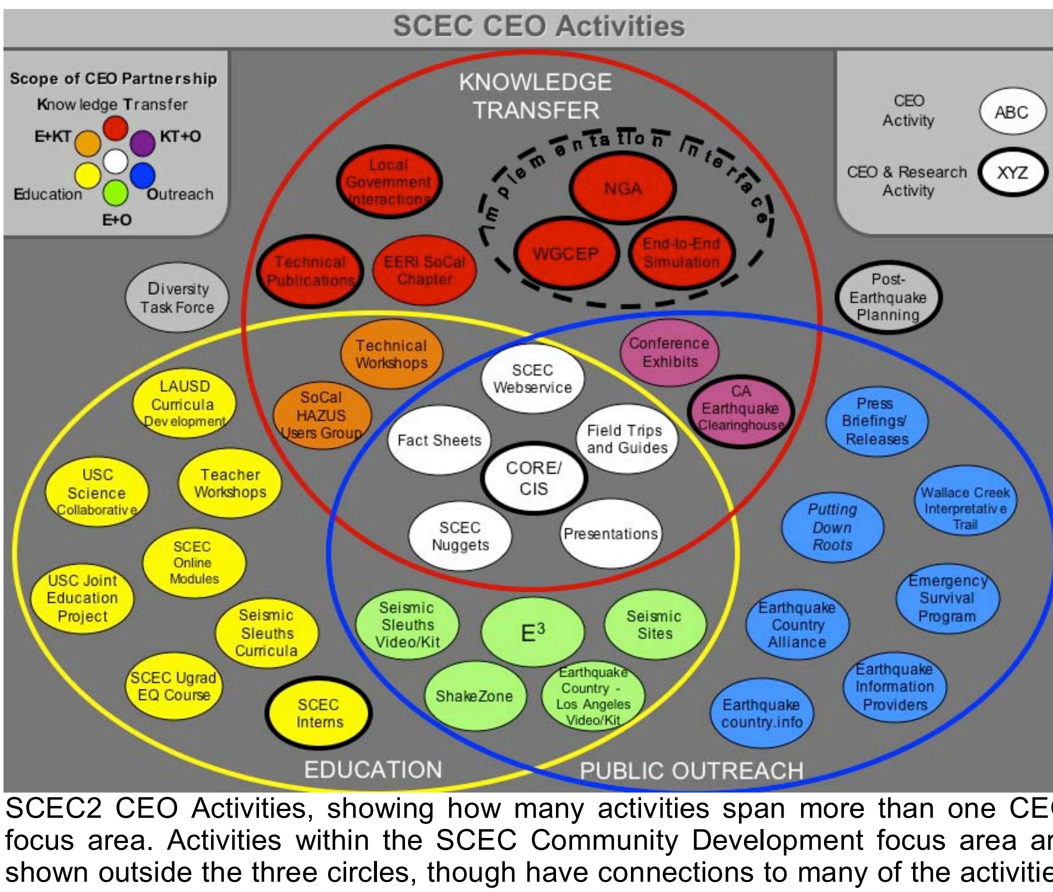
V. SCEC Communication, Education and Outreach (CEO) program

During SCEC2, The *Communication, Education, and Outreach* (CEO) program pursued four long-term goals:

- Coordinate productive interactions among a diverse community of SCEC scientists and with partners in science, engineering, risk management, government, business, and education;
- Increase earthquake knowledge and science literacy at all educational levels, including students and the general public;
- Improve earthquake hazard and risk assessments; and
- Promote earthquake preparedness, mitigation, and planning for response and recovery.

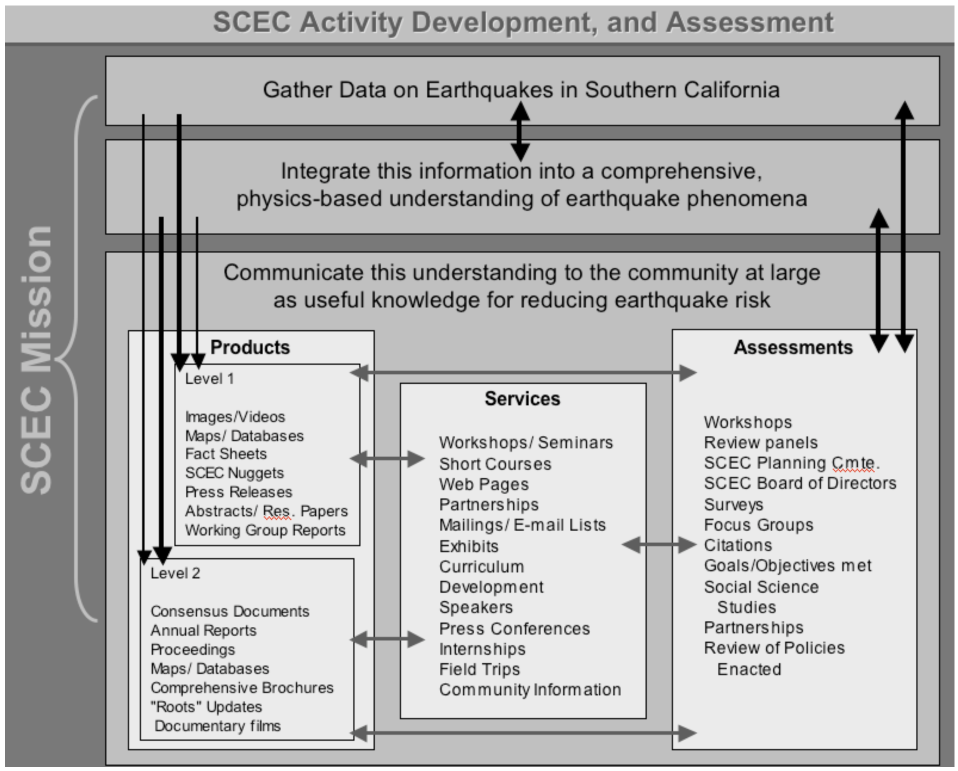
These goals were identified through several workshops involving SCEC scientists and our partner organizations, who were also involved in developing and fulfilling CEO short-term objectives through activities organized within four CEO focus areas: *education* programs and resources for students, educators, and learners of all ages; *public outreach* activities and products for the general public, civic and preparedness groups, and the news media; *knowledge transfer* activities with practicing professionals, government officials, scientists and engineers (with research partnerships coordinated within the SCEC *implementation interface)*; and *SCEC Community development* activities and resources for SCEC scientists and students. Many activities span more than one CEO Focus area.



SCEC2 CEO Activities, showing how many activities span more than one CEO focus area. Activities within the SCEC Community Development focus area are shown outside the three circles, though have connections to many of the activities shown.

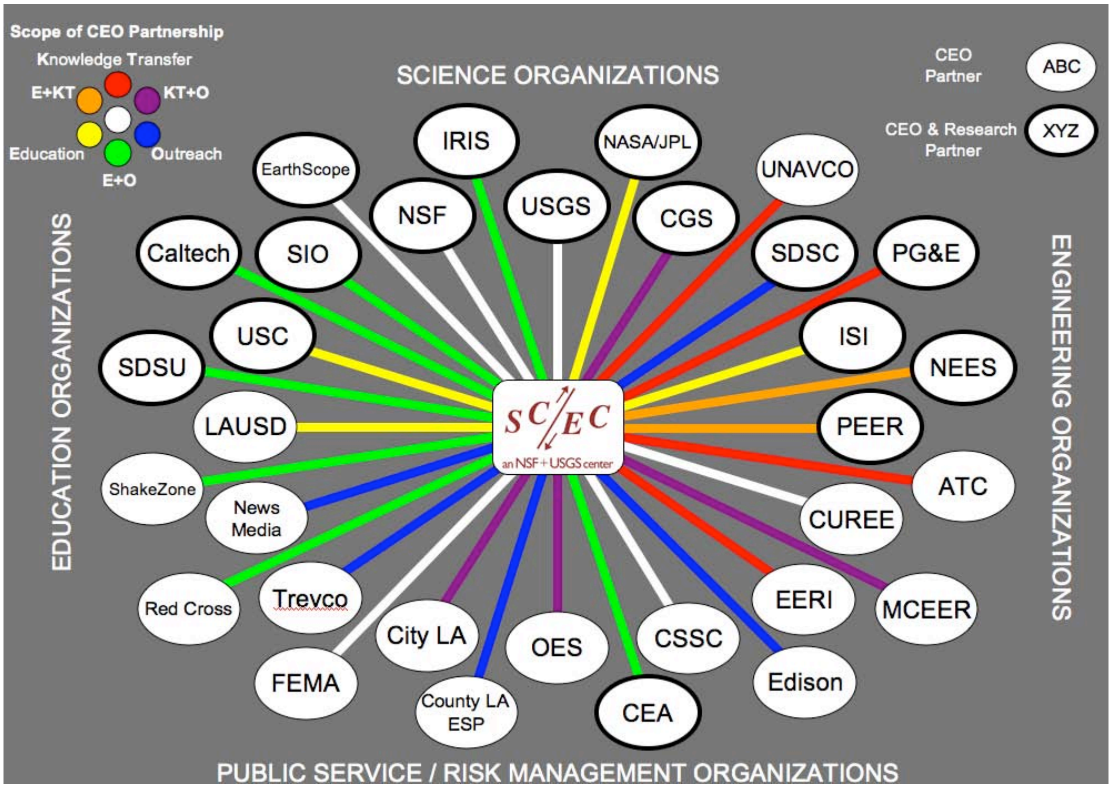
CEO staff also participated in the development of SCEC short-term research objectives and evaluation of proposals received each year in order to develop products and services needed by our various audiences. The list of CEO activities is long and SCEC's organizational relationships are often complex, but we emphasize that the Center's resources, including its staff time, were allocated through a prioritization process that maintained good alignment between the CEO and science objectives. For example, the yearly revisions to the CEO plan were articulated within the revised SCEC Science Plan, published each October, which solicits annual proposals from the SCEC Community; the proposals that responded to the CEO solicitation were evaluated along side the science proposals in the collaboration-building process managed by the Planning Committee.

SCEC Activity Development and Assessment process relative to the SCEC Mission. Both initial data gathering activities and integrated research results create or support a broad range of products and services. Assessments of these products and services



A key aspect of SCEC's success have been the many partnerships that have been sustained to achieving SCEC's mission, research objectives, and outreach goals. These partners include: other science organizations such as IRIS, EarthScope, and UNAVCO; engineering organizations such as PEER, CUREE, and EERI; Education organizations such as Los Angeles County Unified School District, USC Family of Schools, museums, and the National Association of Geoscience Teachers (NAGT); and Public Service / Risk Management organizations such as California Office of Emergency Services, the California Earthquake Authority, FEMA, and the American Red Cross. The image on this next page shows some of these organizations, and the scope of the CEO activities with each (Education, Outreach, Knowledge Transfer, or combinations thereof).

SCEC has developed a particular style of how to partner with these organizations, with four main tenets: 1) minimize promotion of our institutional identity in order to secure buy-in of partners into a larger effort; 2) work towards fulfilling our partners' missions; 3) encourage leadership and broad participation within many levels of the partnership; and 4) don't stress rigid organizational structures. Generally this "lead by supporting" style has worked quite well for SCEC as a science collaboration as well as in SCEC's CEO partnerships.



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Education Activities

SCEC and its expanding network of education partners are committed to fostering increasing earthquake knowledge and science literacy at all educational levels, especially K-12 and college-level education in Earth science.

Objectives

The SCEC2 objectives for the Education focus area were to (1) interest, involve and retain students in earthquake science, (2) develop innovative earth-science education resources, (3) offer effective professional development for K-12 educators.

Results

SCEC Undergraduate Internship Program. SCEC has provided internships to over 190 students since 1994, with 141 during SCEC2 (2001-2006). SCEC interns are typically paid a stipend of $5000 over the summer with support from the NSF REU program. SCEC offers two summer internship programs, SCEC/SURE, and SCEC/USEIT. These programs are the principal SCEC *framework* for undergraduate student participation in SCEC, and have common goals of increasing diversity and retention. In addition to their research projects, participants come together several times during their internship for orientations, field trips, and to present posters at the SCEC Annual meeting. Students apply for both programs at http://www.scec.org/internships.

The *SCEC Summer Undergraduate Research Experience (SCEC/SURE)* has supported students to work one-on-one as student interns with SCEC scientists since 1994. The goals of SCEC/SURE are (1) to provide hands-on experiences for undergraduates and expand student participation in the earth sciences and related disciplines, (2) to encourage students to consider careers in research and education, and (3) to interest, train, and retain talented students, including women, members of underrepresented minorities, persons with disabilities, and students outside the earth sciences. SCEC/SURE has supported students to work on numerous issues related to earthquake science including the history of earthquakes on faults, risk mitigation, seismic velocity modeling, science education, and earthquake engineering. From 1994 through 2006, SCEC provided SURE 121 internships (51 in SCEC2) to 113 students (8 students had 2 internships). 83 SCEC scientists were mentors to these students (several were mentors repeatedly). Of the 113 SURE students, 60 were women and 18 were underrepresented minorities. Since 2005, when we began gathering additional information, there were 17 SURE students, 11 were women, 6 were underrepresented minorities, 8 were first-generation college students, and 2 were from schools with no research opportunities.

The *SCEC Undergraduate Studies in Earthquake Information Technology (SCEC/USEIT)* program, unites undergraduates from across the country in an NSF REU Site at USC. SCEC/USEIT interns interact in a team-oriented research environment with some of the nation's most distinguished geoscience and computer science researchers. The goals of the program are: (1) to allow undergraduates to use advanced tools of information technology to solve important problems in interdisciplinary earthquake research; (2) to close the gap between two fields of undergraduate study--computer science and geoscience; and (3) to engage non-geoscience majors in the application of earth science to the practical problems of reducing earthquake risk. USEIT involves 20 or more undergraduates per summer and now has nearly 80 alumni from more than 30 universities and colleges. It has matured into a successful program with an experienced staff, substantial facilities, well-developed recruitment and longitudinal tracking systems, and performance evaluation mechanisms that are effective and improving.

Summer interns interact in a collaborative, team-oriented, interdisciplinary research environment and are mentored by some of the nation's most forward-thinking earthquake and computer scientists. Research activities are structured around "Grand Challenges" in earthquake information technology. Each summer the interns build upon the foundation laid by previous sessions as they design and engineer increasingly sophisticated visualization tools. The current software, SCEC-VDO (Virtual Display of Objects), is now in wide use by SCEC scientists.\

Since Summer 2002, 79 students in computer science, engineering, geoscience, cinema, economics, mathematics, architecture, communications and pre-law majors have participated in the SCEC/USEIT program. Overall, 37% of USEIT interns have been women, 19% percent have come from ethnic minorities that are traditionally under-represented in the physical sciences and engineering, and 15% percent have been first-generation college students. In the latest summer program (2006), 50% of the interns were women and 45% were under-represented minorities.

<u>Electronic Encyclopedia of Earthquakes (E3).</u> This digital library of educational resources and information was developed during SCEC2 with our partners CUREE and IRIS with initial funding from the NSF National Science Digital Library (NSDL) initiative. The initial goal was to provide information and resources for over 500 earth science and engineering topics with links to

curricular materials useful for teaching and learning about earth science, engineering, physics and mathematics. The drafting of these encyclopedia entries proved quite challenging, however an extensive collection of resources was created and is now shared with the NSDL.

E3 is intended to be a valuable portal to anyone seeking up-to-date earthquake information and authoritative technical sources, and is a platform for cross-training scientists and engineers and will provide a basis for sustained communication and resource building between major education and outreach activities.

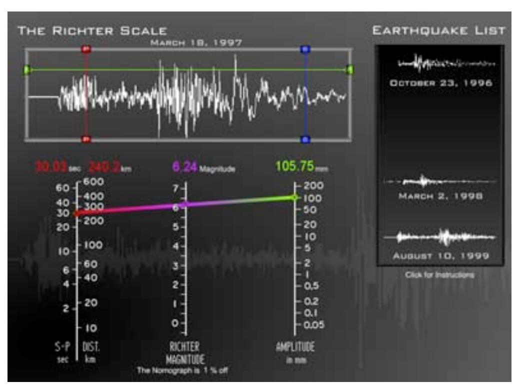
E3 is the the primary SCEC *framework* for presenting extensive earthquake science and engineering information, including curricular materials and technical information organized by topical areas. E3 is used to organize materials for SCEC teacher workshops, field trips, exhibits, and other SCEC activities. A sophisticated information system for building and displaying the E3 collection and web pages has been developed, now called the SCEC Community Organized Resource Environment (SCEC/CORE). This content development and management system has now been used to create many other web *and print* resources, such as the main SCEC website and the new version of the *Putting Down Roots in Earthquake Country* brochure.

In late 2005, the decision was made to partner with Wikipedia for content for the E3 overview sections (the longer encyclopedia-like summaries of each topic). A former SCEC student employee is now one of the top Wikipedia developers, and is helping SCEC parse in Wikipedia content related to earthquakes. We will be then encouraging the SCEC community and other earthquake experts to use the Wikipedia system for creating and revising content, rather than SCEC attempting to write the material at the right level and completeness, which has proved far more involved than originally expected.

In early 2007, the project was renamed *Earthquake Education Environment*, to allow more flexibility in the scope of information provided. Encyclopedia entries will still be included, however additional structures will now be included that will provide an integrated, multimedia online environment where one can obtain educational resources, as well as foster a community of content developers and users. Examples include: teacher guides for standards-based earthquake education that link content standards to their relevant *Encyclopedia* entries and to recommended lesson plans, visualizations, and other resources; content (presentations, kiosks, websites, etc.) created for use by Community Based Organizations, businesses, and others needing to communicate earthquake information to their constituents, with links to *Encyclopedia* entries when background information is needed; and interactive tools that present earthquake education in informal settings such as science centers and natural history museums, which will also build on the extensive content of the *Encyclopedia*.

<u>SCEC's Regional Seismicity and Geodesy Online Education Modules.</u> These interactive online learning resources are based on seismic data from the SCEC data center, and geodetic data from the Southern California Integrated GPS Network (SCIGN). The modules are used by high school and undergraduate students and teachers, and will be integrated with the Electronic Encyclopedia of Earthquakes) (http://www.scecdc.scec.org/Module and http://scign.jpl.nasa.gov/learn). During SCEC2, a project led by Lisa Grant (UCI), Ralph Archuleta (UCSB) and Debi Kilb (Scripps) with SCEC staff updated functionality and content of several activities within the Seismicity module.

<u>Teaching Aids for University and College Level Classes: Visual Objects and QuickTime Movies</u> [managed by Debi Kilb, UCSD/IGPP] Teaching modules were specifically designed to meet the needs of faculty members at SCEC based institutions that can be used in undergraduate and graduate classes and provide an introduction to 3D interactive exploration of data. At the 2003 SCEC meeting many of the visual objects were previewed and netted a favorable response (12 people asked for follow up information). Some of the end products (e.g., QuickTime movies, interactive 3D data sets, image galleries) are currently accessible through a web-based digital library interface at the Visualization Center at Scripps Institution of Oceanography.



<u>Seismic Sleuths Revision.</u> SCEC CEO staff have been working to revise the AGU/FEMA Seismic *Sleuths* middle school earthquake curriculum to reflect advances in science and technology since the last update in 1995. The objectives are to promote and improve natural hazard education for students; to foster preparedness for natural hazards through empowerment and encouraging personal responsibility; to provide an updated and redesigned learning tool that can be easily integrated into a curriculum based on national standards; and to provide constant

updates in science content, pedagogy, and resource information through an interactive website. Each unit has been streamlined and can stand-alone in print or on the Internet in order to be used in a variety of environments. In addition, a television special (*Earthquakes: Seismic Sleuths*) based on the series has been created and aired worldwide, made possible by funding from the California Department of Insurance, the Institute for Business and Home Safety, and SCEC. The hour-long video was first broadcast on "Assignment Discovery" in spring, 2001. The video can be used by teachers as an excellent advance organizer, or viewed by interested citizens who want to learn more about earthquakes, the destruction they can cause, the scientists and engineers who study them, and what they can do to prepare. (http://school.discovery.com/lessonplans/programs/earthquakes-gettingready/q.html)

Teacher Workshops. During SCEC 2, several full-day professional development workshops were offered each year. The workshops provided a connection between developers of earthquake education resources and those who use these resources in the classroom. The workshops included: content and pedagogical instruction; ties to national and state science education standards; and materials teachers can take back to their classrooms. Activities included: the Dynamic Plate Puzzle; Seismic Waves with Slinkys; Brick and Sandpaper Earthquake Machine; and a Shake Table Contest. At the end of the day teachers received an assortment of free materials provided by IRIS, including posters, maps, books, slinkys, and the binders with all the lessons from the workshop included. Workshops were offered concurrent with SCEC meetings, at National Science Teachers Association annual meetings, and at USC.

In 2003 SCEC began a partnership with the SIO Visualization Center to develop teacher workshops. Facilities at the Visualization Center include a wall-sized curved panorama screen (over 10m wide). This allows the workshop participants to be literally immersed in the images being discussed. For example, when the traditional 2D maps of earthquake epicenter data were viewed in 3D, the teachers immediately understood that the faults depicted by the earthquake locations were 3D planes, not 2D lines. Four workshops have now been held with SIO, and will continue each summer. (www.scec.org/education)

USC Science Education Collaborative. Since 2003, SCEC greatly increased engagement with the inner-city neighborhoods around USC to form various partnerships in order to improve science education and increase earthquake awareness in the local community:

- One of these partnerships was with USC's Joint Education Project (JEP), which sends USC students into local schools to teach eight one-hour lessons pertaining to what they are learning in their classes. SCEC, in partnership with the USC department of Earth Sciences, now provides educational resources to JEP students in several earth-science courses, and trains the students how to use the resources in their lessons.
- Another USC-area related partnership was with the Education Consortium of Central Los Angeles (ECCLA), which funded three-week intersession programs in inner-city Los Angeles. SCEC revised and added additional materials to their existing earthquake curriculum, which was renamed "Earthquake Explorers." SCEC also provided educational materials, and arranged guest speakers and field trips.
- SCEC also partnered with JEP, USC Mission Science, USC Sea Grants and the Jet Propulsion Laboratory (JPL) to create hands-on workshops for teachers at schools in the neighborhoods surrounding USC.

Sally Ride Science Festivals. Attended by over 1000 middle school (grades 5–8) age girls at each venue, Sally Ride Science Festivals offer a festive day of activities, lectures, and social activities emphasizing careers in science and engineering. Since 2003 SCEC has presented workshops for adults and students and participated in the Festival's "street fair," a popular venue for hands-on materials and science activities. At the street fair SCEC demonstrates key concepts of earthquake science and provides copies of Putting Down Roots in Earthquake Country. The workshops, presented by female members of the SCEC community share the excitement and the many career opportunities in the Earth sciences. At every festival IRIS has provided SCEC with posters, fact sheets, and other materials to use in the workshops and at the street fair. SCEC has participated annually at the festivals held at Caltech and California State University Los Angeles.

<u>National Association of Geoscience Teachers Far Western Section 2004 Annual Meeting</u>. SCEC hosted this meeting with the USC Earth Science Department the last weekend of February 2004. The teachers in attendance ranged from elementary school teachers up through community college professors. A reception for the teachers began the meeting on Friday evening, which was followed by talks given by Tom Henyey and Tom Jordan, past and present directors of SCEC.

On Saturday, teachers chose one of three all day field trips: Faults of Los Angeles, led by James Dolan, The Geology of the Palos Verdes Peninsula, led by Tom Henyey, and Oceanography and Coastal Geography led by Steve Lund. The meeting banquet was held Saturday evening with Lucy Jones as keynote speaker. Dr. Jones spoke about earthquake prediction, followed by a question and answer session for the teachers. On Sunday the teachers had a choice of an all day earthquake education workshop or one of three half day field trips: The La Brea Tar Pits, Southern California Integrated GPS Network, or the California Institute of Technology Seismology Lab.

<u>ShakeZone</u>. In partnership with the KidZone Youth Museum CUREE, SCEC created an educational, family-oriented exhibit on earthquakes ("ShakeZone") that opened in January 2002. The mission of the exhibit is to reach the local community, particularly the 20,000 elementary school children who visit KidZone each year, with positive messages about studying Earth and preparing for earthquakes. The exhibit presents information about science, engineering, safety and mitigation. A shake table, an interactive computer display, and wall displays teach the visitors about the tools and techniques of earth scientists, engineers and emergency services personnel. The initial exhibit closed in fall 2005. SCEC collaborated with the museum to develop a smaller but updated exhibit based on Putting Down Roots in Earthquake Country which opened in September 2006. The new exhibit features materials and displays provided by the Scripps Institution of Oceanography, the Birch Aquarium at Scripps, CUREE, Caltrans, and the Southern California Gas Company. During summer 2007 the exhibit was used during a series of science week summer camps. In the fall of 2007 KidZone will debut its in- school earthquake programs and an expanded offering of facilitated museum earthquake programs (http://www.kidzone.org).

<u>Other Museum Activities.</u> SCEC has worked with many museums and other informal education venues to develop content and programs for earthquake education. Examples included: advising the development of exhibits ("Structures" at the California Science Center in Los Angeles, "Earthquake! Life on a Restless Planet" at the Scripp's Institution of Oceanography Birch Aquarium in San Diego, "Along the Faultline" at the Exploratorium in San Francisco, and "Quakes from Space" at the American Museum of Natural History in New York); providing materials and tours for the Los Angeles Natural History Museum "Adventures in Nature" summer camp; supporting "Earth Science Week" activities at the Orange County

Discovery Center, Santa Barbara Natural History Museum, and elsewhere; and screening the "Earthquake Country–Los Angeles" video at the San Diego Natural History Museum.

Use of SCEC Community Modeling Environment (CME) Products in K-12 education. SCEC has included CME animations in its teacher education workshops since 2002 with the initial visualization of the Community Fault Model, and through 2007 with the latest Terashake animations. Our "Earthquake Country – Los Angeles" DVD and *Putting Down Roots* handbook are used by teachers throughout Southern California, and both feature CME products. A compilation of CFM visualizations have also distributed on a CD, at teacher conferences such as the National Science Teachers Association annual meeting. Also, a supplement module to an earth science textbook (being developed by a publisher) will lead students through analysis of earthquakes using Terashake animations.

Use of SCEC Community Modeling Environment (CME) Products in Higher education. SCEC faculty (and many others) are using CME animations in there undergraduate and graduate courses. Many graduate students have been supported by the CME project and have key in the development of many CFM products. However, the major impact of the CME and related activities however has been in the SCEC *Undergraduate Studies in Earthquake Information Technology (UseIT)* program, which has developed LA3D and now SCEC-VDO to visualize the SCEC CFM, earthquakes, and other features. This has resulted in a very useful tool but more importantly involved students from computer science, engineering, economics, film, and many other majors in earth science applications of advanced computer science. Several have changed their career paths and are pursuing graduate degrees with SCEC.

Assessment

Education programs in SCEC2 have greatly expanded the Center's ability to provide earthquake information and resources for students and teachers across the country through online resources (E3, SCEC Seismicity Module, etc.) and museum partnerships.

The SCEC2 Intern programs grew each year, and with the advent of the SCEC/UseIT program, SCEC brought students to research and/or the earth sciences who had no previous interest, including many underrepresented minority students. In terms of attracting more students to degrees in the earth sciences, one student changed from an astrophysics major to a geology major, and two computer science undergraduates are now pursuing graduate degrees in geophysics. Through extensive recruitment activities in 2005 and beyond, we hope to continue to offer research opportunities to well-qualified and diverse students from around the country.

However, due to a focus on public outreach activities during SCEC2 (see next section), less time was available to offer additional teacher workshops, develop as many curricular materials as originally planned, and establish partnerships with educational organizations on the same scale as our partnerships in other CEO focus areas. Building upon the resources developed in SCEC2, and expanding their geographic reach, is a priority of the SCEC3 education effort.

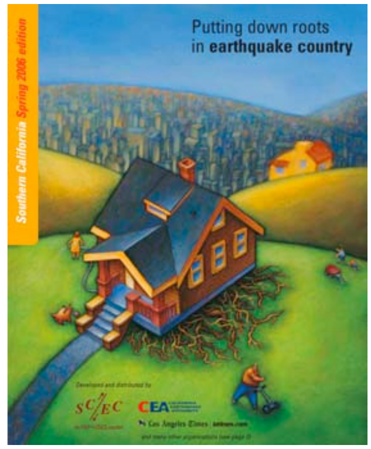
Public Outreach Activities

This Focus Area involved activities and products for media reporters and writers, civic groups and the general public, and was a high priority during SCEC2. Much of 2003 was focused on planning activities and developing products for the 10-year anniversary of the Northridge earthquake in January 2004. These activities have continued into 2007 with product revisions and continue interactions with public outreach partners.

Objectives

The SCEC2 objectives for the Public Outreach Focus Area were to (1) provide useful general earthquake information, (2) develop information for the Spanish-speaking community, (3) facilitate effective media relations, and (4) promote SCEC activities.

Results



Putting Down Roots in Earthquake Country. In 1995 the Southern California Earthquake Center (SCEC), US Geological Survey (USGS), and a large group of partners led by Lucy Jones (USGS) developed and distributed 2 million copies of a 32-page color handbook on earthquake science, mitigation and preparedness. Funding was primarily from the National Science Foundation and USGS. The booklet was distributed through libraries, preparedness partners, cities, companies, and directly to individuals through SCEC.

For the 10-year anniversary of the Northridge earthquake, a new version was produced by SCEC and the newly-formed Earthquake Country Alliance. The updated handbook features current understanding of when and where earthquakes will occur in Southern California, how the ground will shake as a result, and descriptions of what information will be available online. The preparedness section is now organized according to the "Seven Steps to Earthquake Safety." These steps provide a simple set of guidelines for preparing and protecting people and property.

200,000 copies were printed in January 2004, with funding from the California Earthquake Authority (CEA) and FEMA, and another 150,000 copies were printed in September 2004, with funding from CEA, USGS, Edison, Amgen, Quakehold, and others. In Spring 2005 a further revision was printed (60,000 copies) with coupons for home mitigation products. And in the largest new printing yet, in Spring 2006 1.5 million copies of another update were printed, with 1.3 million copies distributed via the *Los Angeles Times* as a "topper"- the booklet was bound on the cover of the Sunday, April 9, newspaper (rather than being lost amid other inserts). Copies of the document have been distributed at home improvement centers (on tables with preparedness products), by the American Red Cross (at neighborhood safety trainings), and by many others. A small printing for Spring 2007 of 100,000 copies will allow SCEC to fulfill requests for copies until the next major revision, which will be printed and distributed in September, 2007, thanks to continued support from the CEA. The updated handbook is now at www.earthquakecountry.info/roots as an online version and downloadable PDF, and printed copies can be ordered for free through an online request form.

A notable acheivement in early 2006 was the first-ever Spanish version of *Putting Down Roots*. A team of Spanish-speaking scientists, emergency managers, and educators worked together to translate the text. 100,000 copies are now being distributed in Southern California. In Spring 2007, a new printing of 600,000 copies (funded by CEA) were distributed through *Hoy* (LA Times Spanish-language newspaper), the Los Angeles Mexican Consulate, and other venues, with media promotion on TV and Radio.

Putting Down Roots is the principal SCEC framework for providing earthquake science, mitigation, and preparedness information to the public. The "Roots" framework extends beyond the distribution of a printed brochure and the online version. For example, the Birch Aquarium in San Diego developed an earthquake exhibit which featured a "Seven Steps" display, and the Emergency Survival Program (managed by LA County) will be basing it's 2006 campaign around the "Seven Steps." In October 2004 over 15,000 copies were included in the Earth Science Week packets distributed to science teachers and others nationwide.

The new version of *Putting Down Roots* was designed to allow other regions to adopt its structure and create additional versions. The first is a Greater San Francisco Bay Area version produced by a partnership led by the USGS with SCEC, local and state emergency managers, the Red Cross and many other organizations. The handbook was revised with Bay Area hazards and a new section called "Why Should I Prepare?" was added that includes scenarios for likely damage, casualties, etc., and how life will change during a large earthquake in the region. Over 750,000 copies were printed in September, 2005, with funding from the California Earthquake Authority, USGS, FEMA, Red Cross, OES, CGS, and several others). 500,000 of these copies (with an inserted coupon for furniture straps and other mitigation products) were distributed in the San Francisco Chronicle. The handbook is available at home improvement stores throughout the Bay Area, and is being distributed by the Red Cross and USGS. Because of high demand a second printing in October, 2005, produced another 130,000 copies for distribution by the USGS and in stores. To commemorate the Centennial of the 1906 San Francisco earthquake, an additional one million copies were printed and distributed in many Bay Area newspapers, the USGS, and other partners, along with a calendar of activities for the anniversary. In Spring, 2007, 500,000 more copies were printed (with minor updates, including a new "Seven Steps" image). The Bay Area booklet can also be accessed from www.earthquakecountry.info/roots. All printings of the Bay Area version to date have been coordinated through SCEC.

The latest development has been the creation led by USGS with many Bay Area partners of a new booklet in the Putting Down Roots series, featuring primarily the "Seven Steps" content and produced in two versions- English and Spanish in one booklet, and English, Chinese, Korean, and Vietnamese in another booklet. This new product is titled *Protecting Your Family From Earthquakes– The Seven Steps to Earthquake Safety*. Developers included the American Red Cross, Asian Pacific Fund, California Earthquake Authority, Governor's Office of Emergency Services, New America Media, Pacific Gas and Electric Company, U.S. Department of Homeland Security Federal Emergency Management Agency, and U.S. Geological Survey. The CEA, FEMA, and others provided funding for 640,000 copies of the English-Spanish version and over 360,000 copies of the English and Asian languages version, with printing coordinated through SCEC. A multi-language media campaign in early 2007 promoted the distribution of the booklets.

Earthquake Country Alliance. To coordinate activities for the 10-year anniversary of the Northridge Earthquake in January 2004 (and beyond), SCEC led the development of the "Earthquake Country Alliance" (ECA). This group was organized to present common messages, to share or promote existing resources, and to develop new activities and products. The ECA includes earthquake scientists and engineers, preparedness experts, response and recovery officials, news media representatives, community leaders, and education specialists. The mission of the ECA is to:

- inspire responsibility for community earthquake safety and recovery;
- increase awareness, preparedness, mitigation;
- improve response and recovery planning;
- reduce losses in future earthquakes.

The ECA is now the primary SCEC framework for

Earthquake Country **Alliance**
We're all in this together.

maintaining partnerships and developing new products and services for the general public. The group first met in June 2003 to begin coordinating plans for the Northridge earthquake anniversary, resulting in a complementary set of activities that commenced in January and continued throughout the year, as follows:

- Jan. 7: "Earthquakes 101." A seminar for the news media, 8 am to noon, Caltech
- Jan. 13: California Emergency Services Association special seminar at CSUN. Speakers included Don Manning, Lucy Jones, and Tom Heaton
- Jan. 15: City of Los Angeles annual emergency response exercise (Northridge scenario)
- Jan. 15-16: Multidisciplinary Center for Earthquake Engineering Research (MCEER) Annual Meeting, at the New Otani Hotel in downtown Los Angeles.
- Jan. 15: Meeting of the California Seismic Safety Commission, Pasadena.
- Jan. 16: "10 years since Northridge: A Special Event for Movers and Shakers." An invite-only luncheon hosted by the Multidisciplinary Center for Earthquake Engineering Research (MCEER), the Southern California Earthquake Center (SCEC), and the Business and Industry Council for Emergency Planning and Preparedness (BICEPP). FEMA and the National Center For Crisis and Continuity Coordination (NC4) sponsored the event. Speakers discussed what has been learned since Northridge and what should be known in the near future.

- Jan. 17: "Northridge Earthquake 10th Anniversary: Learning from the Past, Planning for the Future." Beckman Auditorium on the Caltech Campus, 9 am to 3:30 pm. Lectures, movies, displays and activities about earthquakes, for the general public.
- Feb. 4-8: EERI Annual Meeting, Omni Hotel, downtown Los Angeles. Sessions presented what has been learned since Northridge, and several tours to downtown landmarks were offered.
- Other conferences throughout the year also commemorated the anniversary, such as the Seismological Society of America annual meeting in April (Palm Springs) and the National Earthquake Conference (FEMA, USGS, and many other earthquake organizations) in September (St. Louis, MO).

The ECA has continued to coordinate public awareness efforts in southern California through these and additional products and activities since 2004, especially the yearly updates of *Putting Down Roots in Earthquake Country*. In 2006, the centennial anniversary of the 1906 San Francisco earthquake was commemorated and the Alliance participated in educational activities and events with partners in the Bay Area.

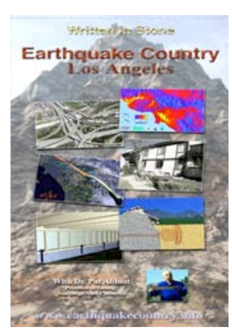
In Summer, 2006, members of the ECA began to organize the *Dare to Prepare* Campaign, to achieve widespread awareness and preparedness goals to mark the 150th anniversary of the January 9, 1857, Ft. Tejon earthquake on the San Andreas fault. With a strategy of getting southern Californians to "talk about our faults," the campaign acknowledges that "Shift Happens," and if you "Secure Your Space" you can protect yourself, your family, and your property. If you live in earthquake country, secure your space by strapping top-heavy furniture and appliances to walls, adding latches to kitchen cabinets, and securing TVs and other heavy objects that can topple and cause serious injuries. Homes and other buildings should be retrofitted if necessary. These and other actions will greatly reduce your risk of damage or injury, and limit your need for community resources after the next earthquake.

On January 9, very close to the end of SCEC2, a major press briefing was held to kickoff *Dare to Prepare*, including local, state, and federal government representatives, SCEC scientists, and ECA partners. A new website (www.daretoprepare.org) was announced, along with other components of the campaign:

- *First Friday Focus*: development of topical campaign materials (prior to the first Friday of each month, April through December) for use by Alliance partners, the news media, and others;
- *Movers and Shakers*: leadership group of prominent Southern California elected officials, business and community leaders, and others;
- *Local activities*: public events throughout the region (presentations, preparedness fairs, etc.), including demonstrations of *Big Shaker*, a large portable earthquake simulator;
- *Media campaign:* television, radio, and print promotion, PSAs, on-air interviews, etc. (Fall)
- *Putting Down Roots in Earthquake Country*: distribution of millions of copies of this comprehensive earthquake science and preparedness handbook;
- *Great Southern California Shakeout*, a regional public earthquake exercise planned for 2008;

Earthquake Country Alliance Website. SCEC developed and maintains this web portal (www.earthquakecountry.info.), which provides multimedia information about living in earthquake country, answers to frequently asked questions, and descriptions of other resources and services that ECA members provide. The portal uses technology developed for the E^3 project (see above). Each ECA member can suggest links to their organization's resources as answers to questions listed on the site. The site is set up separately from the main SCEC web pages (though has attribution to SCEC) so that all members of the ECA see the site as their own and are willing to provide content. The site features the online version of *Putting Down Roots* and special information pages that all groups can promote, such as a special page about the "10.5" miniseries and a page about the "Triangle of Life" controversy (see assessments below).

SCEC Webservice. SCEC's webservice presents the research of SCEC scientists, provides links to SCEC institutions, research facilities, and databases, and serves as a resource for earthquake information, educational products, and links to other earthquake organizations. In 2000 SCEC introduced SCEC News to provide a source of information in all matters relevant to the SCEC community – to disseminate news, announcements, earthquake information, and in-depth coverage of earthquake research. (www.scec.org)



Earthquake Country- Los Angeles. This video was produced by Dr. Pat Abbott of SDSU as the second in his "Written in Stone" series. The video tells the story of how the mountains and valleys of the Los Angeles area formed, including the important role of earthquakes. The video features aerial photography, stunning computer animations, and interviews with well-known experts. The video features 3D fault animations produced by SCEC's "LA3D" visualization system. In addition to conducting several focus groups with teachers and preparedness experts where the video was evaluated, SCEC is also developing curricular kits for school and community groups to accompany the video, and has added captions in both English and Spanish.

These kits will be duplicated in large quantities with funding from the California Earthquake Authority. The Los Angeles Unified School District has asked SCEC to train teachers how to use these curricular kits, and may include the video in a new sixth-grade Earth science curricula soon to be adopted district wide.

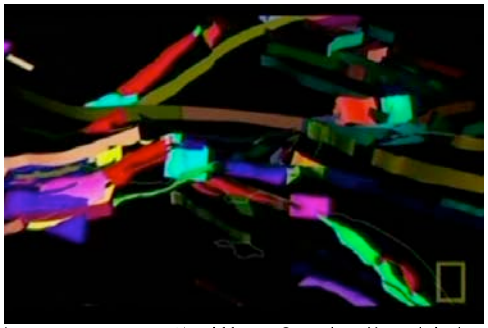
Emergency Survival Program SCEC serves on the Coordinating Council of the Los Angeles County-led *Emergency Surival Program*, with emergency managers from all southern California counties, many large cities, the American Red Cross, and Southern California Edison. The primary role of the program is to develop a series of public information materials including monthly Focus Sheets, newsletter articles, and public service announcements related to a yearly theme. In 2006 the program focused on earthquakes, with seven of the monthly focus sheets based on the "seven steps to earthquake safety" in *Putting Down Roots in Earthquake Country*. SCEC provided the Spanish version of the seven steps text also, and coordinated the translation of the five other monthly focus sheets for 2006.

Media Relations. SCEC engages local, regional and national media organizations (print, radio and television) to jointly educate and inform the public about earthquake-related issues. The goal has been to communicate clear, consistent messages to the public–both to educate and inform and to minimize misunderstandings or the perpetuation of myths. For example, at the SCEC 2004 Annual Meeting a multi-topic press conference was held to provide SCEC's perspective on recent earthquake predictions, discuss large earthquakes on the San Andreas fault, and announce new results from the SCEC TeraShake project. And in May 2005, CEO organized a major press briefing to announce the results of a study of losses expected from a range of earthquakes on the Puente Hills fault (www.scec.org/puentehills) which received broad regional, national, and international coverage. SCEC CEO encourages scientists who are interested in conducting interviews with media reporters and writers to take advantage of short courses designed and taught by public information professionals.

Wallace Creek Interpretive Trail. In partnership with The Bureau of Land Management (BLM), SCEC designed an interpretive trail along a particularly spectacular and accessible 2 km long stretch of the San Andreas Fault near Wallace Creek. Wallace Creek is located on the Carrizo Plain, a 3-4 hour drive north from Los Angeles. The trail opened in January 2001. The area is replete with the classic landforms produced by strike-slip faults: shutter ridges, sag ponds, simple offset stream channels, mole tracks and scarps. SCEC created the infrastructure and interpretive materials (durable signage, brochure content, and a website with additional information and directions to the trail). BLM has agreed to maintain the site and print the brochure into the foreseeable future. (www.scec.org/wallacecreek)

SCEC Publication Distribution. Copies of SCEC's field trip guides, technical reports (Phase I & II reprints, Liquefaction and Landslide Mitigation Guidelines reports, etc.), and *Putting Down Roots in Earthquake Country* general public handbook (see below) are widely distributed at workshops, earthquake preparedness fairs, and through the SCEC website. (www.scec.org/resources/catalog)

Use of SCEC Community Modeling Environment (CME) Products. Many SCEC CME products are being used in public presentations, webpages (scec.org, earthquakecountry.info, etc.), printed publications such as *Putting Down Roots in Earthquake Country* (English and Spanish), our "Earthquake Country – Los Angeles" DVD ("LA3D" animations) and in other venues to communicate earthquake hazards and encourage preparedness. These products, including the SCEC Terashake simulations, Puente Hills earthquake simulation, and Community Fault Model (CFM), have also had extensive media coverage through press briefings, reporters attending the



SCEC Annual Meeting, and television documentaries, and have been used frequently as background imagery in many news stories. Each earthquake simulation is not just a scientific hypothesis, but a visualization of a potential real earthquake that could cause extensive damage and loss of life beyond what has been experienced in southern California previously. SCEC CME visualizations help the public understand how the shaking they may experience will be very intense, and how long it will last. These visualizations were featured extensively in the National Geographic Channel documentary "Killer Quake," which presented SCEC Terashake and Puente Hills animations, along with SCEC VDO fault movies.

Assessment

The public outreach products developed, updated, and maintained during SCEC2 represent a new capacity for providing earthquake-related information and services. During SCEC3, these resources will allow SCEC and our partners to provide continually updated information in a broad assortment of venues and mechanisms. For example, because of the ECA, a coordinated response was possible during 2004 to several public awareness threats: a mini-series about a "10.5" magnitude earthquake, a widely-reported prediction for an a 6.5 magnitude earthquake in southern California, and a mass-email campaign promoting a (dangerous) alternative to the "drop, cover, and hold on" position all preparedness groups endorse. ECA members were able to direct their audiences to a common webpage for information, rather than creating their own response. The ECA e-mail list has provided a way for members to communicate with a larger group of their peers, and meetings have brought together existing partners and new allies.

During SCEC2 the news media has become increasingly aware and interested in SCEC research and now look to SCEC as an international source of information about earthquakes. After significant earthquakes and major earthquake-related news stories, reporters from around the world call SCEC for interviews. It is essential to carefully manage SCEC's media presence and we plan to continue to build awareness of SCEC as a media resource.

Knowledge Transfer Activities

There is a widely perceived gap between basic earthquake science and its implementation in risk mitigation. SCEC's mission dictates that it work to close this implementation gap with engineers, emergency managers, public officials, and other users of earthquake science. The Knowledge Transfer focus area coordinates these activities.

Objectives

The SCEC2 objectives for the Knowledge Transfer focus area were to (1) Engage in collaborations with earthquake engineering researchers and practitioners, (2) develop useful products and activities for practicing professionals, (3) support improved hazard and risk assessment by local government and private industry, and (4) promote effective mitigation techniques and seismic policies.

Results.

<u>Implementation Interface.</u> A goal of SCEC2 was to establish a closer working relationship with the earthquake engineering community that would be more effective in implementing physics-based hazard and risk analysis. We therefore established a new working group, the *SCEC Implementation Interface* (P. Somerville, leader; R. Wesson, co-leader), as a funded component of the Center's program to promote these partnerships. It coordinated activities with all other

SCEC working groups, particularly the Seismic Hazard Analysis focus group, which was responsible for developing earthquake forecasting models (with the ESP and Fault Systems groups) and intensity measure relationships (with the Ground Motions group).

The objectives of the Implementation Interface were to (1) integrate physics-based seismic hazard analysis (SHA) developed by SCEC into earthquake engineering research and practicethrough two-way knowledge transfer and collaborative research, (2) provide a flexible computational framework for system-level hazard and risk analysis through the OpenSHA platform and the Community Modeling Environment, and (3) interface SCEC research with major initiatives in earthquake engineering, such as the Next Generation Attenuation project and the NSF-sponsored George E. Brown Network for Earthquake Engineering Simulation (NEES).

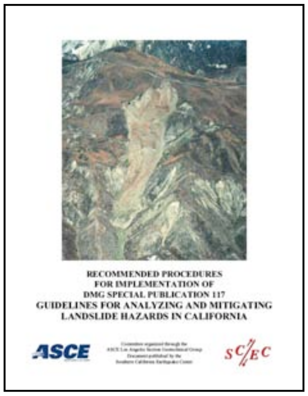
The first initiative was to set up a research partnership with the Pacific Earthquake Engineering Research (PEER) Center and its companion PEER-Lifelines Program. Several efforts were jointly funded by SCEC and PEER, including a large collaboration to study basin effects through wavefield modeling, led by S. Day and a collaboration between A. Cornell and P. Somerville to develop vector-valued probabilistic seismic hazard analysis (VPSHA; Bazzuro and Cornell, 2002). The latter led to a novel application of VPSHA to the use of precariously balanced rocks in PSHA by Purvance et al. (2004).

The activities of the Implementation Interface were broadened through a workshop held in October 2003, which identified end-to-end simulation from the earthquake source through to structural response ("rupture-to-rafters") as a key area for SCEC collaborations with the engineering community. This led to a successful proposal to the California Earhtuqake Authority to support research in this area. SCEC also participated in a project with PEER and others on the study of the impact of large earthquakes on tall buildings.

For a complete description of the results of the Implementation Interface, see Section III.

Open-Source Risk Assessment Workshop To discuss if the open-source concept (a key component of SCEC's OpenSHA project) is appropriate for risk assessment software, SCEC co-sponsored a workshop in March, 2005. Participants included scientists and engineers involved with earthquake, wind, and flood modeling, individuals from reinsurance and commercial risk model companies, and other parties interested in catastrophe risk modeling. Presentations and discussions focused on the need and potential uses for an open-source risk model, on ongoing efforts in earthquake, wind, and flood communities, and on potential next steps. The result was the formation of a new community, organized at http://www.open-risk.org/ and a white paper was produced that outlines next steps.

HAZUS Activities. SCEC2 CEO coordinated the development and activities of the Southern California HAZUS Users Group (SoCalHUG) with the Federal Emergency Management Agency (FEMA) and the California Office of Emergency Services (OES). HAZUS (www.hazus.org) is FEMA's earthquake loss estimation software program. SoCalHUG brings together current and potential HAZUS users from industry, government, universities, and other organizations to (a) train GIS professionals in HAZUS earthquake loss estimation software, (b) improve earthquake databases and inventories, and (c) develop and exercise emergency management protocol. SCEC is considering how it can improve the data and models that HAZUS uses in its calculations, and sees this community as an important audience for SCEC research results. SCEC CEO has organized five general meetings of the user group and several HAZUS trainings. A general meeting and two mini-trainings were held in February, 2006 at the Southern California Association of Governments. A comprehensive four-day training was held in May, 2006, at SCEC headquarters at USC, with six participants trained to be HAZUS "vendors" in the region. (www.hazus.org)



Landslide Report and Workshops. In 1998, a group of geotechnical engineers and engineering geologists with academic, practicing, and regulatory backgrounds was assembled under SCEC auspices as a committee (chaired by Thomas Blake) to develop specific slope stability analysis implementation procedures to aid local southern California city and county agencies in their compliance with review requirements of the State's Seismic Hazard Mapping Act. The work of that committee resulted in the development of a relatively detailed set of procedures for analyzing and mitigating landslide hazards in California (edited by T. Blake, R. Hollingsworth, and J. Stewart), which SCEC published in 2002 and is available on SCEC's web site (www.scec.org/resources/catalog/hazardmitigation.html). In June 2002, over 200 geotechnical engineers, practicing geologists, government regulators and others attended a two-day SCEC workshop that explained the Landslide document. Because of the outstanding response to the sold-out workshop, a second workshop was held in February 2003 for those who were unable to attend the first. The course materials (now available for order) include extensive printed materials including all PowerPoint presentations, and two CDs with software tools and PDF files of all presentations and printed materials. As a bonus, the CD includes PDF files of the presentations given at the 1999 SCEC Liquefaction workshop and both the Landslide and Liquefaction Procedures documents. Plans are now being discussed to offer these workshops in Northern California.

EERI Southern California Chapter. Since 2003, SCEC has hosted the bi-monthly meetings of the southern California chapter of the Earthquake Engineering Research Institute. These meetings include a speaker on a particular topic of interest to the attendees, typically civil, structural, and geotechnical practicing engineers. For example, on November 19, 2003, over 40 people attended a meeting with a speaker addressing new research on "Assessment and Repair of Earthquake Damage in Woodframe Construction," and on January 19, 2005, 20 EERI members attended a briefing on the recent Sumatran earthquake and Indian Ocean Tsunami.

International Earthquake Mitigation and Preparedness SCEC participates with the City of Los Angeles in the international *Earthquakes and Megacities Initiative,* as part of the Americas Cluster which includes Los Angeles, Mexico City, Bogota, and Quito. Each city is represented by emergency managers and academic representatives. The goal of the initiative is to promote the sharing of best practices for earthquake mitigation and preparedness and to develop common resources and joint projects. In addition to developing partnerships with other cities, participation in this program has also strengthened SCEC's ties with the City of Los Angeles. SCEC research results and CEO activities were presented at EMI meetings in Bogota, Colombia in October, 2005, and Quito, Ecuador, in June 2006.

Assessment

Much of the SCEC2 knowledge transfer effort to date has been focused on developing partnerships with research and practicing engineers, and educating the users of technical products. New resources such as OpenSHA and the SCEC Community Modeling Environment greatly expand the services SCEC can provide. SCEC partnerships with earthquake engineering organizations are now very strong, and we expect will continue to develop significant results through joint research projects. These results may lead to safer buildings through improved modeling of ground motions and improved engineering design to accommodate these ground motions. However, such improvements will only become implemented if building codes are updated and local governments regulate construction accordingly. To truly achieve its mission of reducing earthquake risk, SCEC must work at all levels of implementation, from basic research to enforcement of building codes at the local level.

To identify how to strengthen risk communication between SCEC and local governments, L. Grant and E. Runnerstrom of UC Irvine were supported by CEO to study the utilization of seismic hazard data and research products by cities in Orange County, CA. The study focused on evaluating the effectiveness of previous SCEC activities and products in communicating seismic risk at the municipal level. Orange County is well suited for this study because it contains diverse sociologic, geologic, and seismic conditions. In particular, the study looked at the direct use of SCEC products by local-level policy-makers and staff. By understanding the variation in the use of SCEC products, effective areas or targets within cities for risk communication should emerge. Preliminary analyses of the data suggest that SCEC products are underutilized for local planning and seismic hazard mitigation. This may be partly because of nested references within other resources that are non-exclusive to SCEC, and other use of SCEC products without direct citation. The study focused on Safety Elements and related documents (including Technical Background Reports) for Orange County's 34 cities and found that nearly all cities in Orange County relied on planning and/or geotechnical firms to prepare technical reports or Safety Elements. Therefore, these consultants would be excellent targets for seismic risk and hazard communication by SCEC.

SCEC Community Development

The foundation of SCEC CEO is our partnerships and participation in many communities in each of the previous focus areas. Supporting the SCEC community from within is a parallel activity that bolsters our ability to reach out effectively to others. This focus area includes activities and resources relevant to SCEC scientists and students.

Objectives

The SCEC2 objectives for the SCEC Community Development focus area were to (1) increase the diversity of SCEC leadership, scientists, and students, (2) facilitate communication within the SCEC Community, and (3) increase utilization of products from individual research projects.

Results

<u>SCEC Diversity Issues and Possible Activities for a Diversity Task Force.</u> SCEC is committed to supporting the participation of a diverse community of scientists, students, and staff and others. At the beginning of SCEC2, a Diversity Task Force of the Board of Directors was established to identify policies for increasing diversity. This Task Force began by identifying several issues:

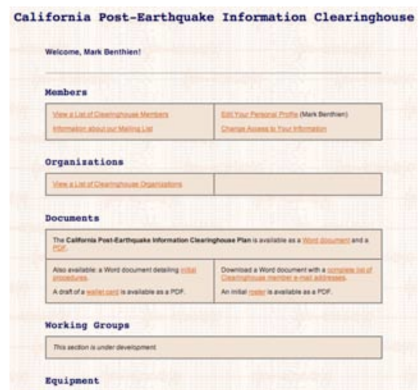
- The leadership of SCEC, including the Officers and the Board, is predominantly white and male.
- The Planning Committee has significant power in SCEC2 and serves as a stepping-stone to leadership. It would be desirable for the planning committee to be significantly diverse.
- Although many women and minority students are involved in intern and other programs at the undergraduate level, successively smaller numbers of women and minorities are involved at the graduate student, post doctoral, junior faculty and senior faculty levels.
- SCEC is a consortium of institutions and as an organization has very little control in hiring scientists and staff, and in admitting students. Diversity goals can be encouraged but not mandated.
- The current situation is not unique to SCEC, but reflects historical trends in the earth and physical science communities.

Several activities to address these issues were identified, including improved demographic assessments of SCEC participants (for a baseline understanding of diversity in SCEC), establishing goals for increasing the numbers of women and under-represented minorities at all levels of SCEC leadership (Board, Planning Committee, etc.), and establishing policy guidelines for the selection of individuals for "stepping stone" opportunities, including speaking at SCEC meetings, and membership on SCEC committees. These activities have been implemented. For 12 years, the SCEC intern program has given research opportunities to studens with diversity as a goal, and long-term tracking shows that many of the under-represented students that participated are still in science careers.

Of the 580+ participants in SCEC2, diversity at various levels seems to reflect historical trends, with much greater diversity among students than senior faculty. In terms of gender, women account for 42% of SCEC undergraduates, 36% of graduate students, 27% of non-faculty researchers, 42% of administrative staff, and 15% of faculty researchers. SCEC has increased the representation of women on its Board of Directors (2 of 15), though board members are appointed by institutions and not selected by SCEC leadership. Three women now participate in the SCEC Planning committee, and SCEC hopes to continue to identify women within each working group willing to take on leadership roles.

Participation of under-represented minorities in SCEC also reflects general Earth science levels, and is generally much lower than preferred at this time. Overall, of the 580 SCEC2 participants, 25 are latino, 10 are Native American, 3 are black, 2 are Pacific Islander, 105 are asian, 413 are white, and 32 are unknown.

Other plans that have been discussed include the establishment of a "sounding board" (a committee of SCEC participants who could serve as informal counselors), holding an evening session at the annual meeting where diversity issues could be aired, developing a mentoring program at a variety of scales (especially at the graduate student, post doc and junior faculty levels), and identifying successful diversity practices of other large science organizations. These and other activities are being considered to continue to support the career trajectories of all members–and potential members– of the SCEC community



SCEC Community Information System (SCEC/CIS). The SCEC CEO team developed a new online database system, using technology developed as part of the Electronic Encyclopedia of Earthquakes project. This system was first implemented to facilitate registration for the 2002 SCEC Annual Meeting, and has since been used for registration for most SCEC workshops and meetings, for tracking SCEC publications, for submitting and reviewing SCEC proposals each year, maintaining demographic information, managing e-mail lists, and for providing access to contact information for each of the 750+ members of the SCEC Community. This system also allows SCEC CEO to better track research projects with potential CEO applications.

As a service for other communities associated with SCEC, similar interfaces have been developed using the same system. Such communities include the California Post Earthquake Information Clearinghouse, the Earthquake Country Alliance, and soon others. Members of multiple communities only need to remember a single password and update their information in one location, to keep their information current for all communities.

Assessment

This is a new area of organized attention in SCEC2, and the structures and mechanisms for achieving the objectives listed above are still in development. Still, SCEC has made progress already in increasing diversity in the community, such as improved representation of women in SCEC leadership positions. The issue of diversity in the sciences extends far beyond SCEC, however since SCEC is a sufficiently large community with significant representation at the nation's leading research institutions, there is an opportunity for SCEC to make a difference.

The objective of increasing the utilization of products from individual research projects (as opposed to products developed from overall SCEC system-level results) has not yet been sufficiently addressed. One new mechanism for promoting awareness of these projects is "SCEC Nuggets," 1-2 page summaries basic research results that were requested for the first time in late 2004. These summaries will also allow SCEC CEO to better identify research projects with potential educational or technical products.

CEO Management Activities

Develop strategic plan. Continue development of long-term strategic plan, with a focus on evaluation strategies. CEO advisory panels (being formed) will be instrumental in providing guidance for evaluation priorities. Careful assessment must be conducted at every stage of program development in order to ensure that the program can be responsive to audience needs and effective in achieving its goals:

1) Stakeholder needs assessment determines a base level of knowledge among various audiences and identify specific needs to be addressed. This information will be gathered through document reviews and interviews with representatives of the key targets audience groups.
2) Evaluation design considers the types of evaluation methodologies and logic models SCEC CEO will employ, based on decisions of what should be evaluated (quality and/or quantity of products? Usefulness of services? Cost-effectiveness?) and why the evaluation is needed (improve the discipline of E&O? Accountability to agency management and stakeholders? Improve service delivery and program effectiveness?)
3) Performance measurement of product development and implementation involves collecting accountability information for stakeholders, tracking intended and unintended outcomes of the program, and providing information vital to program improvement in order to achieve pre-established goals. This information can be useful for management of activities, resources, and partnerships.
4) Programmatic assessment of the overall success in achieving SCEC's stated goals and identification of what was successful, what failed, and why. This step is broader than performance measurement as it addresses the long-term, overall affect of the CEO program as a whole, and has implications for other large-scale E&O programs.

Represent SCEC as Member of:

- Network for Earthquake Engineering Simulation (NEES): EOT Committee
- Earthquakes and Mega Cities Initiative (Los Angeles representative)
- Western States Seismic Policy Council
- California Post-Earthquake Technical Information Clearinghouse
- Emergency Survival Program Coordinating Council
- Southern California HAZUS Users Group
- EERI Southern California Chapter (SCEC hosts bimonthly meetings)
- EERI Mitigation Center So. Cal. Planning Committee
- City of Los Angeles Local Hazard Mitigation Grant Advisory Committee
- County of Los Angeles Local Hazard Mitigation Grant Advisory Committee

Document and Report on CEO activities. Each year many presentations and reports are prepared to describe the activities of the CEO program. In 2003 a paper was published in a special issue of Seismological Research Letters focused on education and outreach.

SCEC2 CEO Team

Staff
Mark Benthien, SCEC associate director for CEO
John Marquis, digital products manager
Bob de Groot, K-12 and informal education programs manager
Sue Perry, executive director, office of experiential learning and career advancement

SCEC2 Student Employees
Monica Maynard, education specialist and Spanish translator (2005-2007)
Ilene Cooper, education specialist (2002-2005)
Ryan de la Torre, web specialist (2006-2007)
Alex Hubbell, web specialist (2005-2006)
Brion Vibber, web specialist (2002-2005)
Ryan Nambu, web specialist (2001-2002)

Consultants
Paul Somerville, Implementation Interface project manager
Hope Seligson, Knowledge Transfer advisor

VI. Advisory Council Report

The membership of the SCEC External Advisory Council is listed in Table VI.1. Sean Solomon continues as the very effective chair of the council. The Advisory Council convened at the SCEC Annual Meeting in September 2006, and their annual report is reproduced verbatim below.

Table VI.1. SCEC Advisory Council for 2006

Sean SOLOMON (Chair), Carnegie Institution of Washington, Washington, DC
Gail ATKINSON, Carleton University, Ottawa, Ontario, Canada
Lloyd CLUFF, Pacific Gas and Electric Company, San Francisco, CA
Jeff FREYMUELLER, University of Alaska, Fairbanks, AK
Patti GUATTERI, Swiss Re-Insurance, New York, NY
Kate MILLER, University of Texas-El Paso, El Paso, Texas
Jack MOEHLE, Pacific Earthquake Eng. Research Center, Richmond, CA
Garry ROGERS, Geological Survey of Canada, Sidney, BC, Canada
Chris ROJAHN, Applied Technology Council, Redwood City, CA
John RUDNICKI, Northwestern University, Evanston, Illinois
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Report of the Advisory Council
Southern California Earthquake Center

Introduction

The Advisory Council of the Southern California Earthquake Center (SCEC) met during the 2006 SCEC Annual Meeting, held in Palm Springs, California, during 10-13 September 2006. The principal meeting of the council was during the evening of 12 September; an earlier session was held prior to the start of the Annual Meeting on 10 September to outline areas of focus. The Council chair summarized the principal Council findings and recommendations in an oral report delivered during the closing session of the Annual Meeting on the morning of 13 September.

For the first time in the memory of those involved in SCEC from its inception, the entire membership of the Advisory Council attended the Annual Meeting. This full attendance underscored the strong support for SCEC activities that is shared across the Council.

On 8 September the SCEC Director had circulated to the Advisory Council a report summarizing how SCEC had responded to Advisory Council recommendations from the previous year and presented a number of new issues warranting council attention. Those new issues included a review of and advice on prioritized scientific objectives for the third phase of the center (termed SCEC3); the development of mechanisms for the sustained evaluation of

SCEC special projects; advice on the scope and scale of SCEC's programs in geodesy; and further advice on issues previously identified by the Advisory Council in the areas of communication, publications, partnerships, and promotion of diversity within the organization.

After a few general remarks below, we discuss the issues raised by the Director in his 8 September mailing, we comment on a number of recurring topics, and we make several recommendations as needed.

Some General Impressions

Because the members of the Advisory Council are not also members of SCEC, the Annual Meeting provides a critical opportunity for council members to assess annual progress on the center's goals and programs. The 2006 meeting and associated workshops proved again to be impressive demonstrations of the energy and enthusiasm of the SCEC community. The 116 registrants who were attending their first SCEC Annual Meeting (28% of the 413 registrants in all) constituted heartening evidence of the center's growing participation and exciting mission.

The Advisory Council lauds the SCEC membership for the persistently selfless spirit with which everyone involved has worked constructively to develop communal, system-level representations that are advancing the goal of end-to-end simulation of earthquake ground motions. SCEC is to be commended for continuing to highlight the most exciting center-fostered work at the Annual Meeting, particularly the work of early-career scientists. The Advisory Council also applauds SCEC's continually developing partnerships with the earthquake engineering community.

The Advisory Council was pleased to see abundant evidence that planning for the transition from the second (SCEC2, 2002-2007) to the third (2007-1012) phase of SCEC was generally at a very mature stage at the time of the Annual Meeting. That such planning extended from organizational structure to research priorities bodes well that the center will proceed smoothly into its new phase.

Scientific Priorities for SCEC3

Both the National Science Foundation (NSF) and the U.S. Geological Survey (USGS) requested that SCEC prepare a revised science plan in which scientific priorities commensurate with anticipated funding levels are presented and defended. SCEC management prepared such a list of prioritized objectives and distilled it at a SCEC Leadership Conference in June 2006 that included the center's Board of Directors and Planning Committee, as well as several agency representatives. That list, so distilled, was discussed further in plenary sessions at the Annual Meeting.

As presented to the Advisory Council and attendees at the Annual Meeting, the 19 "Priority Science Objectives" are arranged hierarchically, with four major objectives, of which two are pre-eminent and fleshed out with subsidiary objectives. Specifically, the development of an extended earthquake rupture forecast (objective #2) and the prediction of broadband ground motions (objective #13) serve as overarching objectives to 15 other objectives. Objective #1 (improving the unified structural representation and employing it to develop system-level models for earthquake forecasting and ground motion prediction) is an ongoing task that provides background information needed for objectives #2 and #13, whereas #19 (preparing post-earthquake response strategies) is an important objective but one where the center will likely not play a lead role.

It is the view of the Advisory Council that the current set of prioritized objectives are an appropriate and complete framework for the center to proceed to the next phase of its mission. A system-level perspective to earthquake science, as SCEC has championed and pioneered, demands that a broad set of objectives be pursued, although not every objective need be addressed at the same tempo or with comparable resources. Moreover, *the prioritized objectives as a suite provide a basis against which investments and achievements can be tracked against milestones attached to individual objectives. In particular, SCEC should associate the proposals it supports (as well as proposals received but not supported) with appropriate current objectives and disseminate that information as one measure of community interest and resource allocation. The council expects that overall the prioritization process will be dynamic, and that within 5 years the current list will have five or more new objectives added.*

Evaluation of SCEC Special Projects

The SCEC3 proposal to NSF and USGS provided a logical framework for assessing progress toward articulated goals, and the center's program in Communication, Education, and Outreach (CEO) has been making efforts to address its progress toward programmatic objectives. Nonetheless, the transition to SCEC3 involves the addition of a number of special projects (e.g., A Petascale Cyberfacility for Physics-based Seismic Hazard Analysis, or PetaSHA; Advancement of Cyberinfrastructure Careers in Earthquake System Science, or ACCESS; and A Collaboratory for the Study of Earthquake Predictability, or CSEP) for which formal procedures for the evaluation of progress will need to be implemented.

SCEC management has requested the assistance of the Advisory Council in the evaluation of these special projects. A specific suggestion from the center Director is that one member of the Advisory Council be designated as liaison to each special project. That liaison member would receive extra briefings at special project workshops and would lead the annual Advisory Council evaluation of project progress. A further suggestion of center management is that a similar liaison be named for advising SCEC on post-earthquake planning.

The Advisory Council is receptive to this invitation in general and looks forward to assisting SCEC management to a greater degree than over the past several years. There was not great enthusiasm within the council, however, for the proposal that individual members be named as formal liaisons to specific special projects. Nevertheless, *the council would be pleased to help track the progress of special projects and other targeted SCEC endeavors by such mechanisms as the participation of individual members or subcommittees in center-sponsored workshops, visits to SCEC, dedicated teleconferences, invitations to special project leaders to make presentations at Advisory Council meetings, or reviews of written progress reports from each project. The Advisory Council is also open to the augmentation of its membership through the* *addition of members with special expertise (e.g., cyberinfrastructure, education) tied to specific projects underway or envisioned.*

SCEC3 Organization

The center's proposed structure for SCEC3 was formalized at the SCEC Leadership Conference in June 2006, and the 2006 Annual Meeting provided the first opportunity for the full SCEC community to review those plans and suggest any needed modifications. SCEC leadership requested that the Advisory Council assist in gathering insight and opinions from the community that might be used to improve this structure, both during the transition from SCEC2 to SCEC3 and beyond.

In general, the Advisory Council regards the changes to the organization envisioned as the center transitions to SCEC3 as sensible ones, and the council received no sense from discussion with attendees at the Annual Meeting that immediate further changes were necessary. *The center should maintain a flexible approach to its organization by which the set of prioritized scientific objectives at any given time drive whatever changes are needed.*

One particular aspect of the center's new organization chart warranted a comment from the Advisory Council. *The Knowledge Transfer activity listed under CEO should not be a delivery "over the wall" to users of SCEC products. Instead, partnerships should be tailored to ensure that maximum use is made of SCEC expertise and accomplishments. The "Tall Buildings Initiative" of SCEC and the Pacific Earth Engineering Research Center (PEER) is an excellent example of such a partnership.*

SCEC3 Programs in Geodesy

The transfer of the Southern California Integrated GPS Network (SCIGN) and Western North America Interferometric Synthetic Aperture Radar (WInSAR) Consortium to other sponsors is now complete. The recent nationalization of the data-gathering activities in geodesy facilities through the EarthScope program has relieved SCEC's burden in managing network operations. Geodesy nonetheless continues to provide a major source of critical observational data for investigations of fault dynamics and earthquakes in southern California. SCEC management has sought the Advisory Council's advice about the appropriate scope and scale of the geodesy programs to be sponsored as part of SCEC3.

The Advisory Council notes that geodesy and crustal deformation are central to at least four of the "Priority Science Objectives" identified for SCEC3 (#3 on defining the slip-rate and earthquake history of the southern San Andreas fault system for the last 2000 years; #4 on the investigation of implications of discrepancies between geodetic and geologic slip rates; #5 on the development of a system-level model for deformation and stress evolution; and #7 on the development of a geodetic network processing system that will detect anomalous strain transients). *Despite the centrality of geodetic themes, as of the time of the Annual Meeting leaders had not been yet named for either the Geodesy Disciplinary Committee or the Crustal Deformation Modeling Focus Group. The Advisory Council regarded these open positions as a* *glaring gap in the preparation for SCEC3. The council suggests that these co-chair positions provide opportunities to expand the participation of women and early-career scientists in SCEC leadership, and we recommend that these leaders be named at the earliest possible time.*

Outside Communication

In its 2004 report the Advisory Council recommended that SCEC enhance the communication of its activities, accomplishments, and plans to the greater Earth science and earthquake engineering communities and to the public. The Advisory Council expanded one aspect of this recommendation in 2005 by calling for the recruitment and support of a cadre of speakers, including early-career scientists, who visit a range of audiences to convey the groundbreaking work that the center has engendered. SCEC has responded by redoubling its efforts to communicate the nature of its programs and findings through technical lectures, public presentations, and media outlets, but SCEC management asked the Advisory Council for further advice on how to project its messages to the outside world and how to make SCEC public relations activities more effective.

The Advisory Council affirms that SCEC's efforts to present its accomplishments to the community and the public have been extensive and laudable, but much of that effort has been made by members of SCEC management. The excitement within the SCEC community, evident to all who attend the Annual Meetings, is still largely invisible to many in the Earth science community and the public. *The Advisory Council regards as still worthwhile its suggestion last year of the establishment of a cadre of speakers, many from the younger elements of the SCEC community. The addition of media training for such speakers would be a good investment. Such a program would advance not only the center's communication objectives but also SCEC's goal to broaden the diversity of the community participating in center activities.*

As a vehicle for communicating SCEC's overall system-level framework for improving our understanding of earthquake physics, the Advisory Council affirmed last year that a monograph, published by the American Geophysical Union (AGU) or another comparably reputable publisher, would provide a needed archival volume to document SCEC's system-level approach to earthquake science as well as a showcase for exciting new results that have been enabled by that methodology. SCEC management put forward to the Board of Directors and Planning Committee the idea for such a comprehensive monograph on SCEC research in earthquake system science, but the response was not sufficiently enthusiastic for the center to take the next step. The Advisory Council was therefore asked its views about the priority and timing of such a publication effort relative to other SCEC activities.

It remains the view of the Advisory Council that documentation of the accomplishments of SCEC2 in earthquake system science remains an important goal, both to communicate to Earth scientists the substantial progress that has been made and to provide a benchmark and a resource for work to follow. Notwithstanding the history of such endeavors by SCEC and the understandably considerable fraction of SCEC leadership time that has recently been devoted to planning and fundraising, the organization of a monograph, collection or papers, or other *vehicle to present SCEC2 accomplishments is a timely and worthy exercise. Leaders for undertaking such an effort should be recruited and encouraged.*

SCEC's Diversity Plan

Last year the Advisory Council lauded SCEC's diversity plan as constituting a serious response to the challenge faced by the entire Earth science community in trying to improve the diversity of participation at all levels. SCEC management takes justifiable pride that its Undergraduate Studies in Earthquake Information Technology (USEIT) program has been particularly successful in promoting diversity among undergraduates involved in SCEC research. Continued advice from the Advisory Council was nonetheless sought regarding mechanisms to promote diversity at other levels within the organization.

The Advisory Council concurs that SCEC's intern program has been a showcase for the involvement of a broad and diverse spectrum of students and that similar attention to diversity is warranted across all other elements of SCEC programs. The council notes that within the identified leadership for SCEC3 there is less gender diversity than there was for SCEC2, and we recommend that this disparity be rectified as new leadership appointments are made. A coordinated set of other activities — possibly including but not limited to the speaker program suggested above, media opportunities, and summer sabbatical visits by faculty from minority institutions and historically black colleges and universities — should be undertaken with the goal of accelerating the achievement of diversity of participation in all SCEC programs.

Final Comments

The Advisory Council is pleased to continue to provide assistance to SCEC in its efforts to formulate and accomplish the center's major goals. At any time the council welcomes comments, criticism, and advice from the seismological community, including individuals and groups both inside and outside SCEC membership, on how best to provide that assistance.

The Advisory Council looks forward to working with SCEC leadership to complete the inauguration of SCEC3 and to help ensure that the products and progress of the center continue to be commensurate with agency and community investment.

Sean C. Solomon, Carnegie Institution of Washington (Chair)
Gail Atkinson, Carleton University
Lloyd S. Cluff, Pacific Gas and Electric Company
Jeffrey T. Freymueller, University of Alaska
Mariagiovanna Guatteri, Swiss Reinsurance America Corporation
Kate C. Miller, University of Texas at El Paso
Jack P. Moehle, Pacific Earthquake Engineering Research Center (PEER)
Garry C. Rogers, Geological Survey of Canada
Chris Rojahn, Applied Technology Council
John Rudnicki, Northwestern University
Ellis M. Stanley, Sr., City of Los Angeles Emergency Preparedness Department

VII. Financial Report

Table VII.1 gives the breakdown of the SCEC 2006 budget by major categories. The list of individual projects supported by SCEC in 2006 can be found on the website http://www.scec.org/research/2006research/index.html.

Table VII.1 2006 Budget Breakdown by Major Categories

Total Funding (NSF and USGS):	$3,747,000
Budgets for Infrastructure:	$ 1,107,000
Management	280,000
CEO Program	380,000
Annual, AC, Board, and PC Meetings	150,000
Information Architect	142,000
Director's Reserve Fund	130,000
SCEC Summer Intern Program	25,000
Budgets for Disciplinary and Focus Group Activities: (including workshops)*	$ 2,640,000
Earthquake Source Physics and FARM	475,000
Ground Motions	290,000
Velocity Structure and Seismology	515,000
Seismic Hazard Analysis	350,000
Fault Systems	580,000
Geodesy	365,000
Workshops	65,000

VIII. Report on Subawards and Monitoring

The process to determine funding for 2006 began with discussions at the SCEC annual meeting in Palm Springs in September, 2005. An RFP was issued in October, 2005 and 180 proposals were submitted in November, 2005. Proposals were then sorted and sent out for review in mid-December, 2005. Each proposal was independently reviewed by the Center Director Tom Jordan, the Deputy Director Ralph Archuleta, by the chair and co-chair of the relevant focus group, and by the chair and co-chair of the relevant disciplinary committee. Reviewers had to recuse themselves where conflicts of interest existed. Every proposal had from 4 to 6 reviews. Reviews were sent to John McRaney, SCEC Associate Director for Administration, who collated and tabulated them. The SCEC Planning Committee (chaired by Archuleta) met on January 19-20, 2005 and spent 25+ hours over two days discussing every proposal. The PC assigned a rating from 1-5 (1 being highest) to each proposal and recommended a funding level. Proposals were rated based on quality of science and the proposed research plan, their relevance to the SCEC 2006 science goals, and the amount of money available for the overall program.

The recommendations of the PC were reviewed by the SCEC board at a meeting on February 8-9, 2005. The board voted 18-0 to accept the recommendations of the PC, pending a final review of the program by the Center Director. The director did not make any changes in the proposed plan approved by the board. The board was given two days to comment on the final plan of Jordan.

SCEC funding for 2006 was $3.747M. The board approved $280K for administration; $380K for the communications, education, and outreach program; $150K for workshops and meetings; and $142K for the information technology program. We also received a $25,000 supplement from NSF for the summer undergraduate intern program.

The Center Director did not give specific targets for funding by infrastructure and science groups. Final funding for each disciplinary and focus group is shown in Table VII.I. Most research in SCEC involves aspects of several focus groups. The funding is shown by primary review group at the Planning Committee meeting.

The Center Director also was given a small ($130,000) fund for supporting projects at his discretion. This funding was used to provide additional workshop support, WGCEP activities, send students to meetings in Greece and Japan, the SCEC3 site review, and CEO activities.

Following this action, individual PI's were notified of the decision on their proposals. Successful applicants submit formal requests for funding to SCEC. After all PI's at a core or participating institution submit their individual proposals, the proposals are scanned and the institution's request is submitted electronically to NSF/USGS for approval to issue a subcontract. Once that approval is received, the formal subcontract is issued to each institution to fund the individual investigators and projects.

Scientific oversight of each project is the responsibility of the Center Director, Deputy Director, and focus/disciplinary group leaders. Fiscal oversight of each project is the responsibility of the Associate Director for Administration. Regular oversight reports go to the SCEC Board. Any unusual problems are brought to the attention of agency personnel.

Subcontracts issued in 2006 are shown in the table below for both the USGS and NSF components of SCEC funding.

Table VIII.1 SCEC Subcontracts for 2006

USGS Funds		
ABS Consulting	20,000	
AIR Worldwide	20,000	
Boston U	10,000	
Cal State-Fullerton	19,000	
Caltech	155,000	Data Center Only
ECI	23,000	
Harvard	215,000	
LANL	26,700	
LLNL	59,000	
Oregon State	10,000	
SPA Risk	20,000	
Stanford	96,000	
UCI	15,000	
Utah State	11,000	
Western Ontario	15,000	
WHOI	15,000	
NSF Funds		
Arizona State	19,000	
British Columbia	16,000	
Brown	38,000	
Caltech	149,000	Science only
Cal State, San Bernardino	35,000	
Case Western	26,700	
Georgia Tech	55,000	
LDEO	43,000	
Michigan	12,000	
MIT	62,800	
North Carolina	27,000	
Oregon	50,000	
RPI	26,500	
SDSU	112,000	
Texas A&M	20,000	
U Mass	35,000	
UCD	10,000	
UCLA	126,000	
UCR	64,000	
UCSB	270,000	
UCSC	41,000	
UCSD	136,000	
UNR	98,000	
URS	59,000	

Report on 2006 SCEC Cost Sharing

The University of Southern California contributes substantial cost sharing for the administration of SCEC. In 2006, USC provided $280,000 for SCEC administration costs, waived $526,000 in overhead recovery on subcontracts, and provided nearly $100,000 in release time to the center director to work on SCEC. USC had previously spent $7,500,000 in 2002-2003 renovating SCEC space.

SCEC Management Cost-Sharing Report for 2006

1. USC annually provides $280,000 in cost-sharing for SCEC management (Direct Costs).

Institution	Amount	Purpose
USC	$222,000	Salary Support of Jordan, McRaney, S. Henyey
	$10,000	Report Preparation and Printing
	$8,000	Meeting Expenses
	$6,000	Office Supplies
	$2,000	Computers and Usage Fees
	$6,000	Administrative Travel Support for SCEC Officers
	$5,000	Postage
	$21,000	Telecommunications
	$280,000	Total

2. USC waives overhead on subcontracts. There are 43 subcontracts in 2006.

$843,000	Amount Subject to Overhead
0.625	USC Overhead Rate
$526,875	Savings Due to Overhead Waiver

3. SCEC Director receives a 50% release from teaching for administrative work.

$100,000	Cost Sharing for 2005-2006 Academic Year

$1,051,875	2005-2006 USC Cost-Sharing to SCEC

In addition to USC support of SCEC management activities, each core institution of SCEC is required by the by-laws to spend at least $35,000 in direct costs on SCEC activities at the local institution. These funds are controlled by the institution's participants in SCEC, not centrally directed by SCEC management. The following table shows how each core institution spent its funds in 2006.

Institution	SCEC Cost-Sharing for 2006 Amount	Purpose
USC	$24,000	Student Support
	$6,000	Research Support/Supplies
	$2,000	Visitor Support
	$3,000	Research Faculty Expenses
	$35,000	Total
Harvard	$25,000	Staff Salaries and Benefits
	$3,800	Student Salaries
	$800	SCEC-Related Travel
	$5,400	Computer Facilities Charges
	$35,000	Total
UCSD	$15,000	Pinon Flat Observatory Operation
	$6,000	CEO Education Workshop
	$20,000	GPS Research
	$9,000	Seismology Initiatives
	$50,000	Total
Columbia/LDEO	$6,715	Administrative Salary Support
	$7,900	Salary Support for Agnes Helmstetter
	$11,590	Salary Support for Felix Waldhauser
	$14,815	Salary Support for Bruce Shaw
	$9,680	Salary Support for Art Lerner-Lam
	$50,700	Total
UCSB	$17,100	Salary Support for Assimaki and Lavallee
	$14,100	Staff Salary Support for Martin (IT)
	$14,900	Student Salaries and Tuition
	$5,300	Supplies and Expenses
	$1,600	Travel
	$2,400	Equipment
	$54,400	
Stanford	$47,000	Graduate Student Fellowships
	$19,000	Graduate Student/Post-Doc Travel
	$66,000	Total

UCLA	$25,000	Salary Support for Research Personnel
	$3,000	Supplies
	$7,000	Travel
	$35,000	Total
MIT	$27,000	Graduate Student Fellowship
	$11,000	Computer Cluster Support
	$6,900	Geophysics Field Camp
	$44,900	
SDSU	$5,855	Computer Hardware
	$3,675	Travel
	$23,115	Student Salary
	$11,774	PI Salary
	$35,000	Total
UNR	$26,000	Salary for Research Faculty Rasool Anooshehpoor
	$12,000	Salary for PhD Student Aasha Pancha
	$38,000	Total
Caltech	$26,000	Two Gutenberg Graduate Student Fellowships
	$48,000	Moore/Richter Graduate Student Fellowship
	$43,000	Housner Graduate Student Fellowship
	$117,000	Total
UCR	$20,000	Computer Equipment
	$25,000	Student Salary Support
	$45,000	Total
USGS/Pasadena	$350,000	Support for SCIGN (Salaries and Materials)
	$127,000	Support for RELM/CSEP (Salaries and Materials)
	$477,000	
USGS/Golden	$150,000	Salary Support of RELM, OpenSHA, NGA Activities
	$10,000	Travel Support
	$160,000	
USGS/Menlo Park	$150,000	Salary Support of SCIGN, SCSN, FARM Activities
	$20,000	
	$170,000	

IX. Demographics of SCEC Participants

Center Database of SCEC Participants in 2006

	Administration/ Technical	Faculty Researcher	Graduate Student	Non-faculty Researcher	Undergraduate Student
Race					
Asian	8	16	34	28	13
Black	1	0	1	1	1
White	43	131	98	187	47
Native American	0	3	6	2	2
No Information	2	1	3	8	2
Ethnicity					
Latino	1	6	13	7	4
Not Latino	44	129	95	178	52
No information	1	11	21	31	6
Withheld	2	3	13	13	3
Gender					
Female	19	25	52	54	33
Male	34	123	84	169	32
Withheld/No Info	1	1	6	2	0
Citizenship					
US	45	116	68	160	54
Other	4	14	50	30	2
No information	5	6	15	15	8
Resident	0	13	4	19	1
Withheld	0	0	5	1	0
Disability Status					
None	43	123	102	177	52
No information	11	27	42	44	13
Hearing	0	1	0	0	0
Visual	0	0	0	2	0
Mobility	0	0	0	2	0

X. Report on International Contacts and Visits

1. SCEC Advisory Council. We have international members of our Advisory Council. Garry Rogers of Geological Survey of Canada, Sydney and Gail Atkinson of Carleton University, Ottawa are members of the council. Atkinson recently moved to the University of Western Ontario.

2. ACES (APEC Cooperative for Earthquake Simulation). SCEC and JPL are the U.S. organizations participating in ACES. Information on ACES can be found at http://www.quakes.uq.edu.au/ACES/. Andrea Donnellan of SCEC/JPL is the U.S. delegate to the ACES International Science Board and John McRaney of SCEC is the secretary general. The fifth ACES workshop was held in April, 2006 in Hawaii. Participants from Australia, China, Japan, Taiwan, and Canada attended.

3. ETH/Zurich. Stefan Wiemar, Martin Mai, and Danijel Schorlemmer of ETH are participants in the SCEC/RELM/CSEP projects.

4. IGNS/New Zealand. Mark Stirling of the Institute for Geological and Nuclear Sciences of New Zealand is involved in the RELM/CSEP program.

5. University of Western Ontario/Canada. Kristy Tiampo of the University of Western Ontario in London, Ontario is funded through the Earthquake Source Physics Group.

6. University of British Columbia/Canada. Elizabeth Klein of UBC is funded through the Fault Systems Group.

7. SCIGN. The SCIGN standing committee was disbanded by SCEC in 2005. SCEC continues to work with UNAVCO to transition maintenance of 125 CGPS stations to be part of PBO. We expect this work to be completed in 2008.

8. SCEC Annual Meeting. The SCEC annual meeting continues to attract international participants each year. There were participants in the 2006 annual meeting from China, Japan, India, Mexico, Canada, France, Switzerland, Germany, Russia, and New Zealand.

10. International Participating Institutions. ETH/Zurich, CICESE/Mexico, University of Western Ontario, and Institute for Geological and Nuclear Sciences/New Zealand; and 4 institutions from Taiwan (Academia Sinica; National Central University; National Chung Cheng University; National Taiwan University) are participating institutions in SCEC.

11. International Workshop on Earthquake Predictability and Time-Depenedent Forecasting. A workshop (co-sponsored by SCEC, Swiss Re, and ETH) was held at Swiss Re near Zurich in January, 2007. Participants from 14 countries attended.

XI. Publications

Note: Publication numbers listed here are continued from the SCEC list that was initiated in 1991. This list includes on research publications that had updates between January, 2006 and January, 2007.

0551 - Li, Y.G., J. E. Vidale, S. M. Day, and D. D. Oglesby, Study of the 1999 M 7.1 Hector Mine, California, Earthquake Fault Plane by Trapped Waves, Bulletin of the Seismological Society of America, Michael Fehler, 92, 4, 1318-1332, 2002.

0595 - Harris, R.A., J.F. Dolan, R. Hartleb, and S.M. Day, The 1999 Izmit, Turkey earthquake - A 3D dynamic stress transfer model of intraearthquake triggering, Bulletin of the Seismological Society of America, 92, no. 1, pp. 245-255, 2002.

0614 - Day, S. M., and G. P. Ely, Effect of a shallow weak zone on fault rupture: Numerical simulation of scale-model experiments, Bulletin of the Seismological Society of America, 92, 3006-3021, 2002.

0677 - Lutter, W.J., G.S. Fuis, T. Ryberg, D.A. Okaya, R.W. Clayton, P.M. Davis, C. Prodehl, J.M. Murphy, V.E. Langenheim, M.L. Benthien, N.J. Godfrey, N.I. Christensen, K. Thygesen, C.H. Thurber, G. Simila, G.R. Keller, Upper crustal structure from the Santa Monica Mountains to the Sierra nevada, southern California: tomographic results from the Los Angeles Regional Seismic Experiments, Phase II (LARSE II), Bulletin of the Seismological Society of America, Seismological Society of America, 94, 2, 619-632, 2004.

0682 - Grant, L. B. and T. K. Rockwell, A northward propagating earthquake sequence in coastal southern California?, Seismological Research Letters, 73, 4, 461-469, 2002.

0687 - Shaw, J. H., A. Plesch, J. F. Dolan, T. L. Pratt, and P. Fiore, Puente Hills blind-thrust system, Los Angeles, California, Bulletin of the Seismological Society of America, Ivan Wong - AE, SSA, El Cerrito, California, 92 , 8, 2946-2960, 2004.

0692 - Favreau, P. and R. J. Archuleta, Direct Seismic Energy Modeling and Application to the 1979 Imperial Valley Earthquake, Geophysical Research Letters, 30, 1198-1202, 2003.

0728 - Abercrombie, R. E., and J. R. Rice, Can Observations of Earthquake Scaling Constrain Slip Weakening?, Geophysical Journal International, 162, 406-424, 2005.

0730 - Anderson, G.J., D.C. Agnew, and H.O. Johnson, Salton Trough regional deformation estimated from combined trilateration and survey-mode GPS data, Bulletin of the Seismological Society of America, 93, 2402-2414, 2003.

0741 - Saichev, A., A. Helmstetter and D. Sornette, Anomalous Scaling of Offspring and Generation Numbers in Branching Processes, Pure and Applied Geophysics, SPRINGER, 162, 1113-1134, 2005.

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